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DEVELOPMENT OF ADVANCED INTERCEPTOR SUBSTRUCTURAL MATERIAL.(U)
JUL 81 N R ADSIT, J HERTZ DAAG46-79-C-0081
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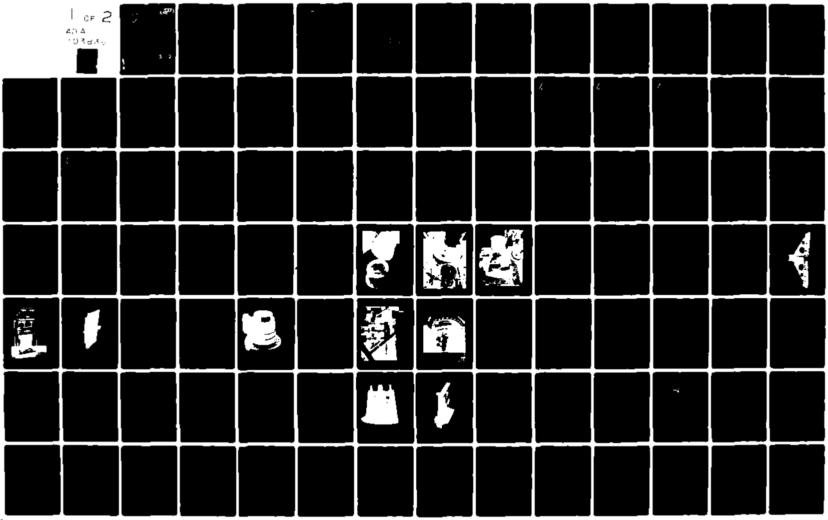

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AMMRC TR 81-32

DEVELOPMENT OF ADVANCED INTERCEPTOR SUBSTRUCTURAL MATERIAL

July 1981

N. R. ADSIT and J. HERTZ
General Dynamics Convair Division
P.O. Box 80847
San Diego, California 92138

FINAL REPORT

Contract No. DAAG46-79-C-0081

Prepared for

ARMY MATERIALS AND MECHANICS RESEARCH CENTER
Watertown, Massachusetts 02172

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Julius Hertz

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Graphite	Epoxy resins	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The work reported herein is aimed at the development of ultra-high-modulus graphite/epoxy structures for use in future advanced terminal interceptors (ATI). ~~This report is a continuation of previous work reported in AMMRC-TR-78-4, TR-78-38~~ and ~~TR-80-44~~. The work has shown that gore section layup used to fabricate interceptor frusta do not effect the strength or modulus of the frusta. Tests on flat panels representative of full thickness joints substantiated that the end joints will carry ATI loads. Finally, two short but

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20. full thickness frusta with antenna window cutouts were fabricated and tested. These frusta met the design goals. Analysis work has been completed and the design and materials are ready for a full-scale demonstration. Toaccomplish this,the preliminary design was reviewed and has been updated. A full-scale tool was designed and has been procured. Finally, a manufacturing process plan for the full-scale frustum was prepared.

PREFACE

This final report was prepared by the General Dynamics Corporation Convair Division for the Army Materials and Mechanics Research Center (AMMRC), Watertown, Massachusetts under contract DAAG46-79-C-0081. This work is part of the program on Development of Hardened ABM Materials, Mr. John F. Dignam, Program Manager. The AMMRC technical supervisor is Mr. Lewis R. Aronin.

This report covers work performed during the period 5 September 1979 to September 1980 by personnel from the General Dynamics Convair Division. Mr Julius Hertz was the program director; Dr. N. R. Adsit, program manager; Mr. Edward E. Spier, Analysis; Mr. Jack Prunty, Design; Mr D. Nirschl and Mr. Steven Maurus, Structural Testing. The frusta test specimens were fabricated by Messrs. Charles M. Ogle, Wayne Woods, Keith C. Gaeth, James Prather.

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SECTION 1

SUMMARY

Lightweight, stiff materials are required for advanced terminal interceptor (ATI) structures. Previous programs performed for AMMRC by General Dynamics have designed and tested several half-scale frusta and joints. Concepts of equipment support rings were also fabricated and tested. The relationship of the work covered in the present report to the overall development effort is summarized in Figure 1-1. A summary of the frusta fabrication and testing is given in Table 1-1.

The objective of this study was to complete the studies to permit the fabrication of full-scale frusta. Tasks included:

(a) Test of the equipment support ring bond joint to failure.

(b) Fabrication and test of coupon specimens with gore splices.

(c) Fabrication and tests of full thickness joint specimens.

(d) Fabrication and test of two full thickness but short frusta that contained cutouts.

(e) Completion of equipment support ring analysis.

(f) Updating of the preliminary frustum design.

(g) Design and procurement of the tool necessary to fabricate the full-scale frustum.

(h) Development of manufacturing plan for full-scale frusta.

Subscale equipment rings have been tested to loads exceeding the expected service load. Failure occurred by shearing as well as in the bond joint.

The gore splice specimens showed that fabrication by layup of gore sections had no effect on the predicted strength or modulus of the specimens. Full thickness flat joint specimens carried the required loads and demonstrated that the ATI frusta joints will carry the design loads. Two full thickness but short frusta complete with antenna cutouts carried the required design loads.

The preliminary frustum design proved to be adequate and has been adopted as the final design. The tool to fabricate full-size frusta was designed and procured.

A manufacturing plan to fabricate full-size frusta has been prepared and is included in this report.

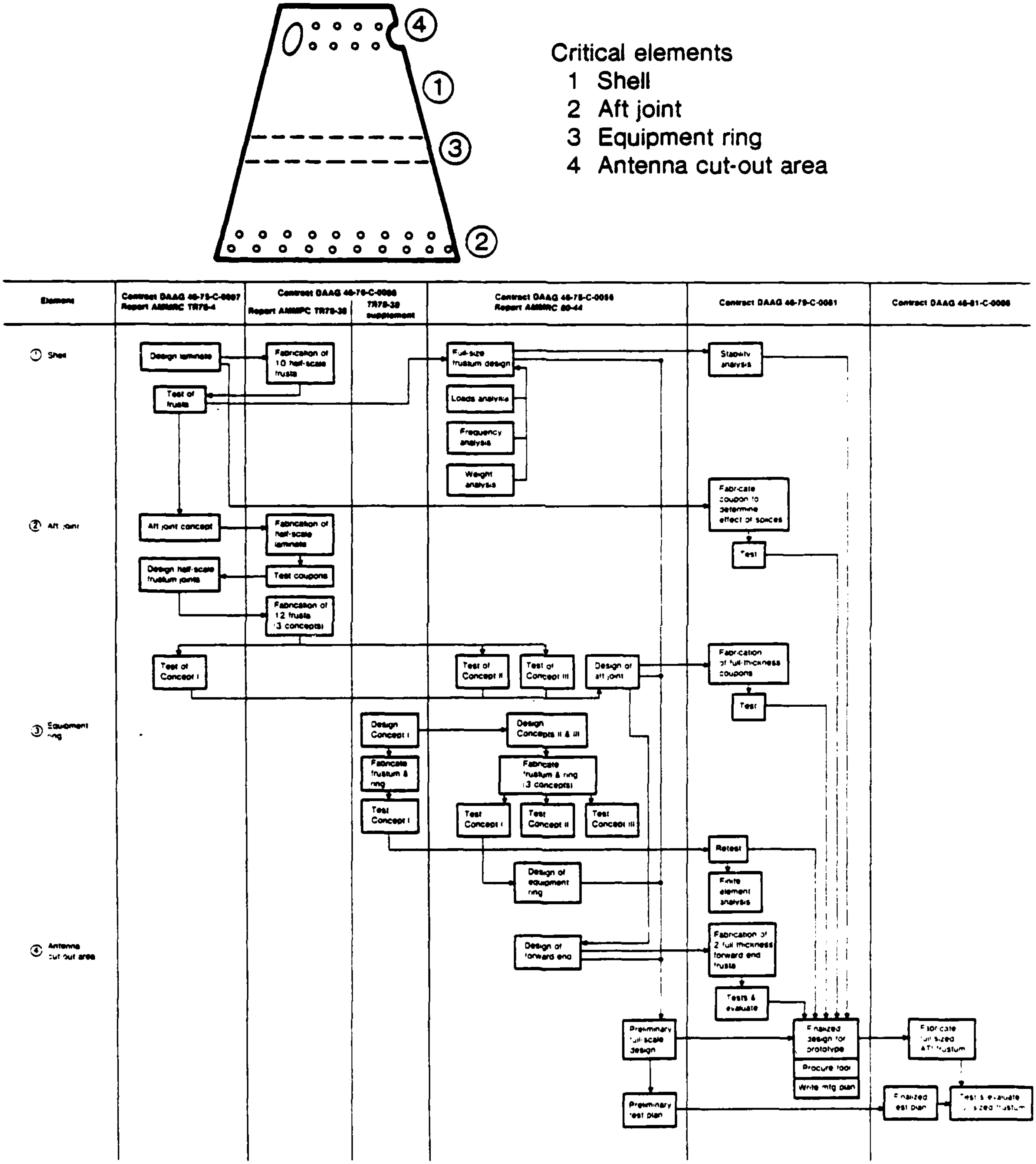

Figure 1-1. Summary Advanced Terminal Interceptor Composites Frustum.

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Table 1-1. Summary of Frusta Tests

Cone No.	Test No.		Reported Fabrication Data	Type of Test	Report Test Data
1	1	Half-Size Basic Frustum*	AMMRC 78-38	Axial Compression	AMMRC 78-4
2	2			Shear Bending	
3	3			Combined	
4	4			Combined & Compression	
5	5			Combined & Moment	
6	6			Axial Compression	
7	7			Combined	
8	8			Combined & Compression	
9	9			Combined & Moment	
10	10			Combined & Compression	
1	01R	Half-Size Aft Joint Conc. I	AMMRC 78-38	Shock	AMMRC 78-4
2	02R	" " " "		Shock	"
3	3A	" " " "		Combined	"
4	4A	" " " "		Shear/Bending	"
7	I	" " " Concept III		Shock	AMMRC 80-44
8	C1	" " " "		Combined	
9	C2	" " " "		Shear/Bending	
10	II	" " " Concept II		Shock	
11 R	C4	" " " "		Shear/Bending	
12	C3	" " " "		Combined	
5		" " " Concept I		Equipment Ring	
6		" " " "		Equipment Ring	
LS-1		Large Scale w/Equip Rng	AMMRC 78-38 Supplement	Equipment Ring	AMMRC 78-38 Supplement & this report
LS-2		"	AMMRC 80-44	"	AMMRC 80-44 & this report
LS-3		"	"	"	"
FF-1		Full Thickness Forward Frustum (Forward 11")	This Report	Combined	This Report
FF-2		"	"		"

*sizes given in Table 1-2

Table 1-2. Summary of Frusta Sizes

	Half Size	Large Size	Full Size
Length, inches	9.30	13.4	33.7
OD forward, inches	7.81	8.54	8.01
OD aft, inches	5.78	10.73	15.41
Thickness, inches	0.190 nom.	0.179 to 0.210	0.380
Cone angle, degrees	6.27	4.67	6.27

SECTION 2

INTRODUCTION

2.1 BACKGROUND

Advanced terminal interceptor (ATI) configuration studies have identified the need for lightweight, stiff missile structures, especially for interceptors designed to engage maneuvering threats. To meet this challenge, the Army Materials and Mechanics Research Center (AMMRC) has conducted research and development on advanced materials including beryllium, metal-matrix composites, and resin-matrix composites. In the last category, ultra-high-modulus (UHM) graphite/epoxy composite structures have been under evaluation and subscale development since 1973 (Reference 1). The results of previous work on UHM materials show significant reductions in launch weight over more conventional materials.

Complementing programs have been performed for AMMRC by General Dynamics Convair Division (References 2 and 3) and Martin Marietta Orlando Division (Reference 1) to pursue the UHM graphite/epoxy conical shell development. Under these programs, ten graphite/epoxy conical frusta were fabricated representing a half-scale version of the aft portion of the guidance and control section of an early ATI configuration. The sizes of these frusta are shown in Table 1-2. These were successfully tested, and the results closely verified analytical predictions. Interleaved titanium foil designs for the end joints were successfully tested using 13 half-scale frusta. An intermediate load introduction ring was designed and analyzed. This resulted in a unique wedge shape ring design of high-strength graphite/epoxy. The fabrication, assembly, and test of such a ring in a "larger size" frustum was accomplished, and the bonded ring joint resisted ultimate design loading at both room temperature (RT) and 325F without failure. After several tests, the ring was tested to failure at RT. This occurred at 260 percent of the predicted design ultimate load. A titanium ring concept also met design requirements, but the wedge shape graphite/epoxy (T-300/934) ring concept was selected because the coefficient of thermal expansion of the T-300/934 more closely matches that of the frustum wall.

Preliminary design (shown in Figure 2-1) and analysis of a full-scale ATI guidance and controls section (reference 4) showed that adequate margins of safety exist for all suspected failure modes. Thermal analysis showed that the interior of the basic frustum is not heated during flight. A manufacturing study (reference 4) showed that it is feasible to produce full-scale ATI guidance and controls sections at a production rate of 1000 articles per year.

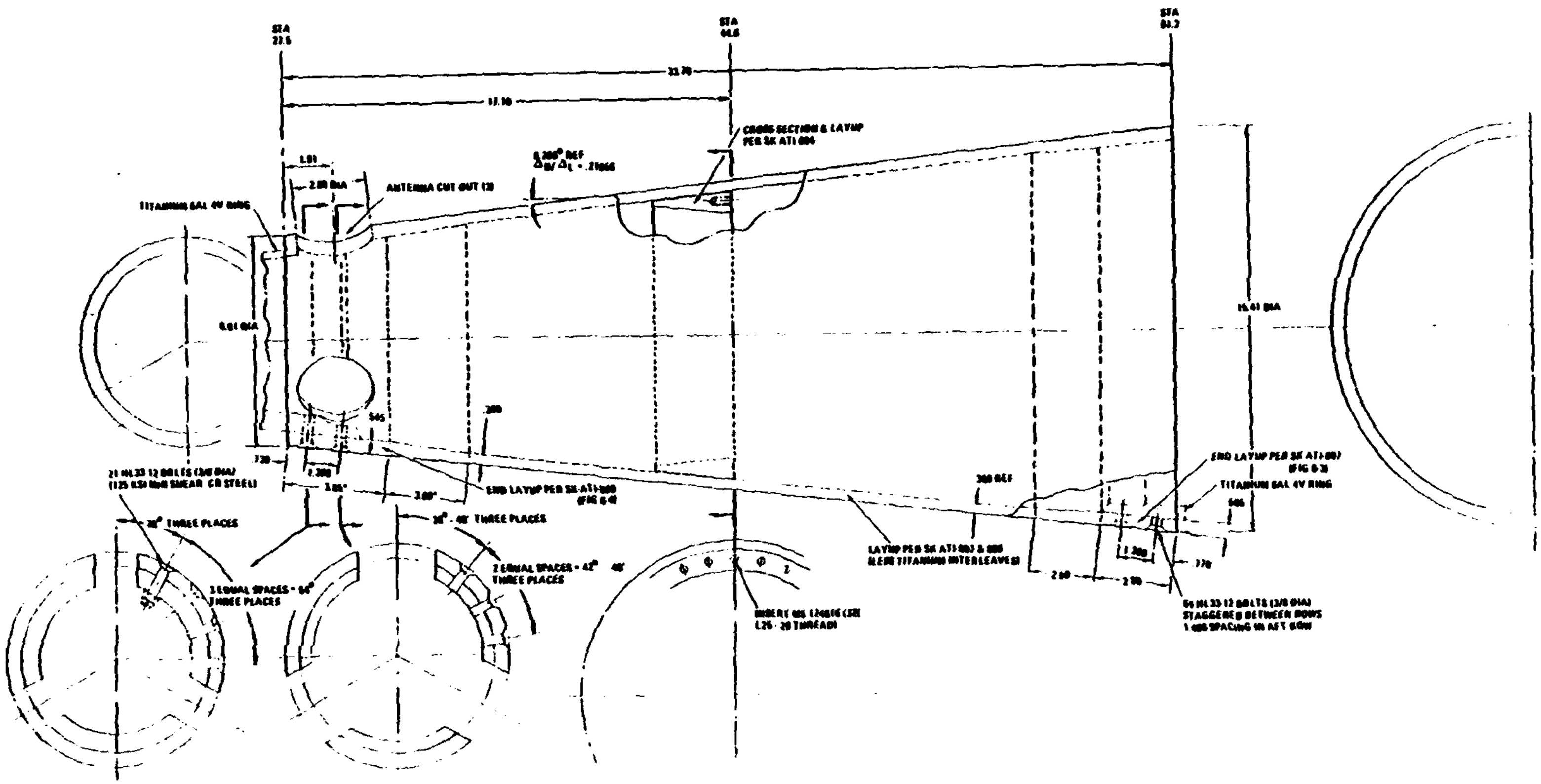

Figure 2-1. Guidance and Control Section Full-Scale Composite Structure

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2.2 PROGRAM OBJECTIVE

The primary objective of the present program and those studies preceding it was to demonstrate the feasibility of using ultra-high modulus graphite/epoxy as a structural material on future high-performance interceptors. This objective was to be demonstrated by analysis, fabrication, and testing of conical frusta representative of a guidance and control section of an advanced terminal interceptor (ATI). An early study (Reference 1) showed that approximately two-thirds of the launch weight could be saved by going from an aluminum ATI to one built from ultra-high-modulus graphite/epoxy. This relationship was developed on the basis that all structural frequencies should be proportionally above the control system bandwidth. This criterion establishes that a first structural bending mode frequency above 70 Hz is required at second stage ignition.

Under an earlier program (Reference 2), General Dynamics qualified an ultra-high modulus graphite/epoxy (GY-70/934) to Material Specification ANA74700314-001, developed a manufacturing process for fabrication of conical frusta using prepreg gore sections laid into and cured in a bulk graphite tool, and developed a manufacturing process for making high-strength joints by interleaving titanium foil between the graphite/epoxy layers in a closed conical shape. Thirteen subscale frusta were successfully built and 12 were subsequently tested. The results demonstrated the feasibility of meeting the primary objective.

Once feasibility of shell fabrication was established, it was necessary to demonstrate the ability to fabricate and assemble a simulated equipment mounting ring for a typical ATI guidance and controls section. Preliminary analysis, fabrication, and testing was conducted as part of contract DAAG46-76-C-0008 (Reference 3). An experimental high-strength (T-300/934) graphite/epoxy wedge ring concept secondary bonded to the inside of the frusta was successfully demonstrated. Helicoils were used for attaching a simulated equipment mounting plate to the ring.

Under contract DAAG46-78-C-0056 (Reference 4), additional detail objectives were met which support the primary objective of proving that UHM graphite/epoxy is a feasible structural material for future ATI. Under this contract, detailed structural and thermal analysis were conducted on the defined full-scale section, additional confirmation tests were run on the wedge ring design, the weight of the structures calculated, a manufacturing analysis was prepared showing the feasibility of producing 1000 guidance and control sections per year, and three-view detail and assembly drawings were prepared for the full-scale ATI section.

The primary objective of the present program was to continue the early efforts in the areas of design, analysis, manufacturing development, and testing while maintaining the end objective, i.e., the use of a graphite/epoxy substructure for an ATI. Detailed tasks of this program were as follows:

(a) Review previous results of subelement and subscale tests for their adequacy to the full-scale design.

(b) Demonstrate load carrying ability and stiffness of the shell at the forward end through a series of subelement and subscale tests simulating the combined effects of antenna holes and joint reinforcements.

(c) Demonstrate adequacy of forward and aft splice attachments.

(d) Test two frusta with equipment rings to fail the bond. Use the data to gain a better understanding of the stress distribution in the ring-to-frustum bonded joint.

(e) Compare subelement and subscale experimental results to analytical predictions.

(f) Update full-scale frustum design using analytical data generated by a minimum of five detailed finite element analyses in critical areas such as end joints and antenna cutouts.

(g) Design and procure necessary tooling to fabricate a full-scale missile body section complete with equipment support ring and reinforced end joints and antenna cutout areas.

(h) Prepare a detailed manufacturing process plan for fabrication of a full-scale frustum.

SECTION 3

MATERIALS

3.1 GRAPHITE/EPOXY

At the outset of this program ultra-high-modulus (UHM) graphite/epoxy (GY-70/934, Fiberite hy-E-1534) prepreg was procured from Fiberite Corporation of Winona, MN. The prepreg was ordered per material specification ANA74700314-001B which was developed by Martin Marietta under AMMRC sponsorship (Reference 1).

The Fiberite certification test data on Lot C9-627 (85.5 pounds) is given in Table 3-1. A summary of prepreg properties obtained at General Dynamics are given in Table 3-2. A unidirectional panel was made from the prepreg using the cure cycle previously reported (Reference 2). Flexure and short beam shear specimens were machined from each panel so that the length of the specimens were in the 0^{o} direction. The specimens were tested at ambient temperature and that data, as well as cured panel resin content, fiber volume, and specific gravity are reported in Table 3-3. As shown in Table 3-2, the percent resin flow was considerably lower than required. There is no known reason for the high flow values reported by Fiberite (Table 3-1) unless they inadvertently ran the tests at 100 psi rather than 50 psi. The material was accepted because the process gel testing indicated that the resin was not excessively advanced, and the cured panel ply thickness was within specification requirements. The Fiberite certification test data for a second lot of 21.9 pounds (Lot CO-285) is given in Table 3-4. The summary of prepreg properties obtained at General Dynamics are included in Table 3-2. A unidirectional panel was made from this prepreg lot, and the data are given in Table 3-5. This lot of material met the requirements of ANA74700314-001B.

3.2 TITANIUM FOIL

Titanium foil is interleaved between the graphite/epoxy layers at the forward and aft joints. For this program, General Dynamics purchased 0.005 in. thick 6Al-4V titanium foil from Chemical Machining Corp. The certification data for this foil is given in Table 3-6. Sheets 12 by 24 inches were prepared with .020 in. diameter holes chemically milled on 0.4 in. centers by Chemical Machining Corp. The purpose of these holes was to facilitate resin and volatile bleeding during layup and cure.

3.3 BOLTS

In order to carry the load at the joints it was necessary to obtain high strength bolts. The bolt selected had to have a minimum shear strength of 125 ksi. HLT53TB-12-16 bolts and HL273DU-12 nuts were purchased from Hi Shear Corp, and were used for the test articles.

3.4 FURNISHED FRUSTA

Two frusta (LS-1 and LS-2) with internally bonded graphite/epoxy equipment rings were furnished by AMMRC. The frusta had been fabricated and tested previously (Reference 4). The initial failure mode was helicoil pullout rather than in the bonds between the equipment rings and the frusta. They were furnished to this program so that the ultimate joint strengths between the equipment rings and the frusta could be determined.

Table 3-1. Fiberite Prepreg Certification Data

hy-E® By FIBERITE

PHONE (507) 454-3611

FIBERITE CORPORATION

CERTIFICATION

MAIN OFFICE 501 WEST THIRD ST.
WINONA, MINNESOTA 55987

General Dynamics
Convair Division
Attn: Accounts Payable
P. O. Box 80818
San Diego, CA 92138

Date: August 27, 1979

ATTENTION: Mr. Bob Mitchell

Gentlemen:

We certify that Fiberite hy-E 1534 tape ordered on your Purchase Order 48-36625 has been tested in accordance with the applicable specification procedures and found to possess the following properties, therefore meeting the requirements of AMA-74700314-001 Rev. B specification.

Quantity Shipped On 8/27/79	85.5#							
Lot No.	C9-627							
Roll No.	1	3	4	5	6	7	8	9
Tape Size, Inches	2.75	2.75	2.75	2.75	2.75	2.75	27.5	2.75
Resin Solids, %	39.5	38.7	40.8	38.2	39.8	40.2	38.0	41.7
Volatile Content, %	0.8	0.5	0.5	0.8	0.5	0.7	0.7	0.5
Laminate Flow, %@ 50 p.s.i.	19.2	15.7	19.4	16.5	17.2	17.9	16.4	18.8
Gel Time, Minutes @ 177°C	7.6	6.9	6.7	7.0	7.0	7.2	6.9	7.0
Tack	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass

Specific Gravity		
Tensile Strength (p.s.i.)		Fiber data attached
Tensile Modulus (10^6 p.s.i.)		I.R. scan enclosed
Flexural Strength (p.s.i.) RT	124,631*	
350°F	113,081*	*Normalized to 63% fiber volume
Flexural Modulus (10^6 p.s.i.)		
Compression Strength (p.s.i.)		
Horizontal Beam Shear (p.s.i.) RT	6,677	
350°F	7,018	
Cured Ply Thickness, Inches	.00480	
Date of Manufacture:	6/17/79	
Shelf Life	6 months @ 0°F Max.	
Ref: Packing List No.:	012617	

Page 1

P. D. THILL
Manager, Quality Control

Winona Printing Co.

Table 3-1. Fiberite Prepreg Certification Data (Con't)

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General Dynamics
Convair Division
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P. O. Box 80818
San Diego, CA 92138
Mr. Bob Mitchell

Date: August 27, 1979

Gentlemen:

We certify that Fiberite hy-E 1534 tape ordered on your Purchase Order 43-36625 has been tested in accordance with the applicable specification procedures and found to possess the following properties, therefore meeting the requirements of ANA-74700314-001 Rev. B specification.

Quantity Shipped On	3/27/79							
Lot No.	C9-627							
Roll No.	10	11	12	13	14	15	16	18
Tape Size, Inches	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75
Resin Solids, %	42.3	40.1	41.6	41.1	37.6	37.4	41.2	37.6
Volatile Content, %	0.5	0.5	0.6	0.6	0.6	0.5	0.5	0.6
Laminate Flow, %@ 50 p.s.i.	19.1	17.4	19.8	19.6	16.4	16.9	19.1	15.4
Gel Time, Minutes @ 177°C	6.9	7.1	7.6	7.7	7.7	7.8	7.1	7.1
Tack	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass

Specific Gravity	
Tensile Strength (p.s.i.)	
Tensile Modulus (10^6 p.s.i.)	
Flexural Strength (p.s.i.)	
Flexural Modulus (10^6 p.s.i.)	
Compression Strength (p.s.i.)	
Horizontal Beam Shear (p.s.i.)	
Cured Ply Thickness, Inches	
Date of Manufacture:	6/17/79
Shelf Life	6 months @ 0°F Max.
~~Ref: Packing List No.:~~	012617

P. D. THILL
Manager, Quality Control

hy-E® By FIBERITE

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Date: August 27, 1979

ATTENTION: Mr. Bob Mitchell

Gentlemen:

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Quantity Shipped On 8/27/79		
Lot No.	C9-627	
Roll No.	19	20
Tape Size, Inches	2.75	2.75
Resin Solids, %	37.2	38.2
Volatile Content, %	0.5	0.5
Laminate Flow, %@ 50 p.s.i.	15.2	15.0
Gel Time, Minutes @ 177°C	6.9	7.0
Tack	Pass	Pass
Specific Gravity		
Tensile Strength (p.s.i.)		
Tensile Modulus (10^6 p.s.i.)		
Flexural Strength (p.s.i.)		
Flexural Modulus (10^6 p.s.i.)		
Compression Strength (p.s.i.)		
Horizontal Beam Shear (p.s.i.)		
Cured Ply Thickness, Inches		
Date of Manufacture:	6/17/79	
Shelf Life	6 months @ 0°F Max.	
Ref: Packing List No.:	C12617	

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Winona Printing Co.

P. D. THILL
Manager, Quality Control

Table 3-1. Fiberite Prepreg Certification Data (Con't)

Lot	Strength (ksi)	Modulus (msi)	Density (g/cc)
ST3/244(29)	262.4	71.1	1.99
244(36)	295.8	72.5	1.97
291(08)	250	75.5	1.98
291(06)	250	75.5	1.98
291(04)	259	78.3	1.97
291(05)	250	75.5	1.99
291(09)	276	75.3	1.99
291(11)	276	75.3	1.97
291(13)	255	75.7	1.99
288(57)	298	78.2	1.98
288(56)	298	78.2	1.99
288(55)	298	78.2	1.98
288(53)	256	74.5	1.99
288(51)	256	74.5	2.00
288(50)	294	80.3	2.00
288(49)	294	80.3	1.98
288(52)	256	74.5	2.00
ST4/299(22)	310	78.2	1.98
299(24)	310	78.2	1.98
299(26)	300	79.0	1.98

Table 3-2. Prepreg Properties for hy-E-1534 Batches Tested by General Dynamics

Batch	% Volatile Content Spec. Req.	% Volatile Content GD Average	% Resin Solids Spec. Req.	% Resin Solids GD Average	% Resin Flow Spec. Req. (50 psi)	% Resin Flow GD Average (50 psi)	% Resin Flow GD Average (100 psi)	Process* Gel	Infrared Analysis	Cured Ply** Thickness Inch
C9-627	2 max	0.7	40 ± 3	38.5	20 ± 5	7.8	15.1	300F	Meets Standard	.0049
C0-285	2 max	0.8	40 ± 3	42.9	20 ± 5	21.6	29.3	305F	Meets Standard	.0048

* Process gel is temperature at which resin gels when prepreg is processed through normal cure cycle.

** Normalized to 63% fiber volume

Material: Gy 70/934
Supplier Designation: hy-E-1534
Laminate Number: A1-1079-S
Orientation: $(0)_{18}$
Lot: C9-627

Fiber Content (Wt. %): 72.5
Resin Content (Wt. %): 27.5
Fiber Volume (%): 62.7
Specific Gravity: 1.71

Table 3-3. Laminate Test Results

Specimen Number	Run Number	Width Inch	Thickness Inch	Area $Inch^2$	Ult. Load Pounds	F_{TU} KSI	E_T MSI	F_{FU} KSI	E_F MSI	F_{SU} KSI
T-1	I-4392	.5045	.0830	.0418	4680	112.0	47.8			
T-2	I-4393	.5050	.0813	.0411	4510	109.7	44.0			
T-3	I-4394	.5042	.0833	.0420	4865	115.8	45.5			
T-4	I-4395	.5034	.0861	.0433	4675	107.9	47.8			
T-5	I-4396	.5027	.0871	.0438	4740	108.2	46.6			
F-1	I-4058	.5038	.0816		99.0			116	37.6	
F-2	I-4059	.5049	.0817		82.5			102	40.9	
F-3	I-4060	.5051	.0819		103.5			121	40.5	
F-4	I-4061	.5041	.0815		104.0			122	38.0	
S-1	I-4062	.2544	.0818	.0208	220					7.93
S-2	I-4063	.2545	.0820	.0209	225					8.07
S-3	I-4064	.2546	.0823	.0210	231					8.25
S-4	I-4065	.2545	.0825	.0210	212.5					7.59
					$\bar{X}$	110.7	46.3	115	39.3	7.96
					N	5	5	4	4	4
					S	3.27	1.62	9.22	1.69	.28
					C_y	3%	3.5%	8%	4.3%	3.5%
					$\bar{X}$*	111.2	46.5	116	39.5	-
					Spec. Req.	80	37	95	34	

*Normalized to 63% fiber volume

hy-E® By FIBERITE

Table 3-4. Fiberite Prepreg Certification Data

PHONE (507) 454-3611

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ATTENTION: Mr. Bob Mitchell

Gentlemen:

We certify that Fiberite hy-E 1534 tape ordered on your Purchase Order 48-36625 has been tested in accordance with the applicable specification procedures and found to possess the following properties, therefore meeting the requirements of ARA-74-700314-001B specification.

Quantity Shipped On 2/5/80	21.9#			
Lot No.	CO-285			
Roll No.	1	2	3	4
Tape Size, Inches	2.75	2.75	2.75	2.75
Resin Solids, %	37.0	38.5	38.2	41.0
Volatile Content, %	0.4	0.4	0.4	0.4
Laminate Flow, % @ 50 p.s.i.	20.9	22.5	17.5	16.3
Gel Time, Minutes @ 177°C.	7.1	7.0	6.9	7.0
Tack	Pass	Pass	Pass	Pass
Drape	Pass	Pass	Pass	Pass

Specific Gravity

Tensile Strength (p.s.i.)

Tensile Modulus (10^6 p.s.i.)

Flexural Strength (p.s.i.) RT 132,551*; 350°F. 103,037*

Flexural Modulus (10^6 p.s.i.)

Compression Strength (p.s.i.)

Fiber Data

Lot	Strength (ksi)	Modulus (msi)	Density (g/cc)
ST-4/293(22)	239	80.9	2.00
ST-4/293(23)	289	80.9	1.99
ST-4/293(25)	242	78.3	1.98
ST-4/293(26)	242	78.3	1.99

* Normalized to 63% fiber volume

I.R. scan attached

Horizontal Beam Shear (p.s.i.) RT	8,240
350°F.	7,896
Cured Ply Thickness, Inches	.00491
Date of Manufacture:	1/24/80
Shelf Life	6 months @ 0°F. Max.
Ref: Packing List No.:	013423

P. D. THILL
Manager, Quality Control

Table 3-5. Laminate Test Results

Material: GY70/934
Supplier Designation: hy-E-1534
Laminate Number: A1-2150-1
Orientation: $(0)_{18}$
Lot CO-285
Roll 1

Fiber content (wt%) 69.36
Resin content (wt%) 30.62
Fiber volume (%) 59.05
Specific gravity 1.72

Specimen Number	Run Number	Width Inch	Thickness Inch	Area $Inch^2$	Ult Load Pounds	F_{TU} ksi	E_T msi	F_{FU} ksi	F_{SU}
T-1	I-808	.5000	.0840	.0420	4620	110.0	45.4		
T-2	I-809	.5007	.0860	.0430	4870	113.3	44.4		
T-3	I-810	.5006	.0872	.0436	4680	107.3	44.4		
T-4	I-811	.4993	.0875	.0437	4850	110.9	44.8		
T-5	I-812	.5010	.0870	.0436	4500	103.2	44.6		
F-1	I-839	.5013	.0880		104.5			113	
F-2	I-840	.5004	.0873		102			112	
F-3	I-841	.5007	.0870		100			111	
F-4	I-842	.5008	.0870		100.5			111	
S-1	I-843	.2500	.0870		187				6.45
S-3	I-844	.2503	.0873		194				6.66
S-5	I-845	.2508	.0874		194				6.64
S-7	I-846	.2512	.0878		195				6.63
					$\bar{X}$	108.9	44.7	112	6.60
					N	5	5	4	4
					S	3.86	.41	.95	.1
					Cv	3.5%	.9%	.9%	1.5%
					$\bar{X}$*	116.2	47.7	119	--
					spec req.	80	37	95	

*normalized to 63% fiber volume

Table 3-6. 6Al-4V Titanium Certification Data

Durkee Testing Laboratories

1520 WEST 178TH STREET • GARDENA, CALIFORNIA 90248
PHONE (213) 321-9800

Chemical Machining Corporation
142 Nevada Street
El Segundo, California 90245

(2) Tensile, and (2) Bend Test Coupons, identified as for .005" x 12" x 12"

For: Parker Hannifin

DATE	LAB NO	YOUR P. O. NO	MATERIAL	SPECIFICATION
1/25/78	E-6030	13008	6AL-4V Titanium	MIL-T-9046H

CERTIFIED REPORT OF PHYSICAL TEST

HARDENED IN FURNACE TEMPERED IN FURNACE

Physical Properties

			YIELD POINT		TENSILE STRENGTH						
	ACTUAL SIZE	ACTUAL AREA	ACTUAL LOAD IN LBS	POUNDS PER SQ IN	ACTUAL LOAD IN LBS	POUNDS PER SQ IN	ELONG IN 2 IN	ELONG %	REDUCED DIMENSION	REDUCT OF AREA %	
L	.0052/.540	.00281	384	136,650	414	147,350	.16	8.0			
T	.0052/.542	.00282	393	139,350	410	145,400	.17	8.5			
MAXIMUM REQUIREMENTS											
MINIMUM REQUIREMENTS				126,000		134,000		8.0			

Bend Test (4.5T Radius, 105°):

L	Satisfactory
T	Satisfactory

Chemical Analysis:

Carbon	.028%
Aluminum	6.10
Vanadium	4.15
Iron	.17
Hydrogen	.0088
Oxygen	.102
Nitrogen	.011
Titanium	Remainder

OUR REC. LOG NO.: Q-4392

ymR

METALLURGICAL TEST

ONE SAMPLE TEST SPECIMEN WAS EXAMINED MICROSCOPICALLY FOR THE FOLLOWING

Carburization Decarburization

MATERIAL conforms TO SPECIFICATION

Respectfully submitted,

Chemist

By

Roy F. Pegram, Gen. Mgr.
DURKEE TESTING LABORATORIES

SECTION 4

FABRICATION

Prior to fabrication of full-thickness frusta,(representative of the forward 11 inches of the full size frustum) two types of laminate test panels were prepared. The first type was a spliced laminate panel to evaluate the effects of splices formed by the use of gore sections in the normal manufacture of frusta. The second type of panel had titanium foil interleaved between the graphite/epoxy plies and was used to simulate the forward and aft joints. Sections 4.1.1 and 4.1.2 describe the fabrication procedures for these laminates and the specimens machined from the respective panels. The procedure for fabrication of two 11-inch long full thickness frusta is given in Section 4.2.

4.1 LAMINATE TEST PANELS

4.1.1 Spliced Laminate

A half-thickness spliced laminate (i.e., half the thickness of the full-sized frustum) was fabricated to evaluate the effects of longitudinal (0°) splices on laminate strength and modulus. The panel was prepared using 38 plies of GY70/934 graphite/epoxy prepreg (described in Section 3.1) and the stacking sequence shown in Table 4-1. Gores of the 0° plies were cut and stacked to the pattern shown in Figure 4-1. Figure 4-2 shows the location from which specimens were machined. This resulted in half of the specimens having splices and half without splices (i.e., control specimens).

The fabrication sequence for the flat laminate was identical to that used throughout this program and preceding programs for making frusta. Large unidirectional sheets of GY-70/934 prepreg were prepared by butting plies of 2.75-inch wide prepreg tape. The prepreg sheets were individually placed between sheets of porous, Teflon-coated glass cloth and held for a minimum of 15 minutes at room temperature under a vacuum bag at a minimum pressure of 29 inches of mercury. After debagging, laminate plies were cut at the proper angles from the large sheets. The longitudinal (0°) plies were cut as required to form the splice joints shown in Figure 4-1. A template was used so that the resulting splices were representative of frusta gore segments. All 0° plies contained the splices in the same location, thereby representing the worst case one might encounter. This is avoided in frusta layup by changing the starting point for each ply. All 45°, 90°, and 135° plies were layed up as uniform, non-spliced plies. The laminate layup tool consisted of an 0.5-inch thick aluminum alloy base plate with 0.5-inch bolted picture frame sides to encase the laminate. A rubber overpress was used on top of the laminate in a similar manner to that used in manufacturing frusta.

A detailed step-by-step procedure for fabrication of the spliced laminate is as follows:

1. Lay up and compact sufficient unidirectional GY-70/934 for all the plies needed in the spliced laminate. Note batch and roll numbers for all prepreg used in the laminate.

2. Cut the 38 plies at the proper orientations as noted in Table 4-1.

3. Apply one ply of porous, Teflon-coated glass cloth to the bottom of the picture frame tool.

4. Lay up plies 1 to 10 per the orientation sequence shown in Table 4-1. All 0° plies shall be cut as shown in Figure 4-1.

5. Apply one ply of porous, Teflon-coated glass cloth over layup to act as a separator film and then apply two plies of style 7581 glass cloth bleeder. Vacuum bag using VacPak or equivalent film.

6. Apply a minimum of 24 inches of mercury and preply at room temperature (RT) for a minimum of 30 minutes.

7. Remove vacuum bag, bleeder cloth, and separator film.

8. Lay up plies 11 to 19 per the orientation sequence shown in Table 4-1. All 0^{o} plies shall be cut as shown in Figure 4-1.

9. Apply bleeder system consisting of one ply of porous, Teflon-coated glass separator film and six plies of style 7581 glass fabric. Apply 1/8-inch thick rubber overpress followed by three plies of style 1534 glass fabric to serve as a vent. Place two thermocouples in the edge of the laminate and one on the tool. Bag for precompaction.

10. Precompact as follows: Apply a minimum of 24 inches of mercury, heat in an autoclave at 2 to 5F/minute to 160 ± 5F, apply 50 ± 5 psig autoclave pressure, hold 15 to 20 minutes and cool under vacuum and pressure to below 100F at a maximum rate of 5F/minute.

11. Remove bag, vent, rubber overpress, bleeder fabric and Teflon-coated glass.

12. Lay up plies 20 to 29 per the orientation sequence shown in Table 4-1. All zero degree plies shall be cut as shown in Figure 4-1.

13. Prepare for preplying per step 5.

14. Preply per step 6.

15. Debag per step 7.

16. Lay up plies 30 to 38 per the orientation sequence shown in Table 4-1. All zero degree plies shall be cut as shown in Figure 4-1.

17. Apply bleeder system consisting of one ply of porous, Teflon-coated glass separator, one ply of style 120 glass fabric, and six plies of style 7581 glass fabric. Apply a 1/8-inch thick rubber overpress followed by three plies of style 1534 glass fabric to serve as a vent. Place two thermocouples in the edge of the laminate and one on the tool. Bag for cure.

18. Cure as follows: Apply a minimum of 24 inches of mercury on the bag at RT, hold for a minimum of 30 minutes, heat the part in autoclave at a rate of 2 to 4F/minute to 250 ± 10F, hold at that temperature for 45 ± 5 minutes, apply 100 psig autoclave pressure in less than 5 minutes, hold an additional 45 ± 5 minutes, heat the part at a rate of 2 to 4F/minute to 350 ± 10F, hold for 120 minutes, and cool the part at a rate not to exceed 5F/minute under vacuum and pressure.

19. Debag and remove part from tool.

Test specimens were then machined to size and labeled per the cutting plan shown in Figure 4-2. The cutting was accomplished using a 60 grit diamond impregnated 10 inch blade at 5600 surface feet per minute. The laminate was clamped to a stationary table, and the blade passed through the laminate at a feed rate of 4 to 6 inches/minute. Deionized water was used as a coolant. Tapered fiberglass reinforced tabs were bonded to the tensile specimens using Hysol's EA934 modified epoxy adhesive. Compression specimens were potted in end blocks using the same adhesive.

4.1.2 Joint Verification Laminates

Two separate laminates were fabricated during this phase of the program, i.e., one representative of the aft joint and the second representative of the forward joint. These laminates contained a combination of GY-70/934 unidirectional tape and 0.005 perforated titanium foil (described in Sections 3.1 and 3.2). Specific laminate compositions represent the full thickness of the joints as shown in the preliminary design (Reference 4) that is:

Laminate	Representative Joint	Plies of GY-70/934	Plies of Titanium
A1-11139-1	Aft Joint	76	25
A1-11199-1	Forward Single Shear Joint	76	33

Each laminate was 12 by 14 inches in size with the zero degree orientation in the 14-inch direction. Full size, non-spliced sheets of titanium were used in conjunction with full sheets of GY-70/934 unidirectional tape. The basic procedure used for each laminate was the same. Because of the different number of plies in the two laminates, precompaction was accomplished at different steps in the fabrication cycle. The procedure for the aft joint laminate will be described in this section. The forward joint laminate had the same number of GY-70/934 and titanium plies as that used in frusta buildup areas. Its description therefore is the same as that detailed in Section 4.2.

The GY-70/934 was not layed up and preplied in flat sheets as has previously been discussed. Because no splice joints were required, the prepreg was layed up a ply at a time directly into the mold. It was necessary to preply the laminate periodically to aid plies in sticking to the previous ply and to help prevent gaps within the individual plies. As with the spliced test laminate, an aluminum picture frame tool was used.

A detailed step-by-step procedure for the aft joint test laminate is as follows:

1. Prepare titanium

   Cleaning: Immerse in solution of OAKITE-HD126 (106 gm/2.5 gallons of water) at 140 to 180F for 5 to 15 minutes. Rinse with tap water at RT.

   Pickling: Immerse for two minutes maximum in solution of 2.0 to 3.0 fluid ounces/gallon HF and 40 to 50 fluid ounces/gallon HNO_3 at RT. Rinse titanium with tap water. Immerse for 1.5 to 2.5 minutes at RT in a solution of 6.5 to 7.0 ounces/gallon $Na_3 PO_4$, 2.5 to 3.0 ounces/gallon of KF, and 2.2 to 2.5 fluid ounces/gallon of 70% HF. Rinse in tap water and follow with a 15 minute soak in deionized water at 145 to 155F.

   Storage: Place processed titanium between lint free cheesecloth and store at RT until ready for use. Note: All titanium to be handled with lint free white nylon gloves.

2. Apply one ply of porous Teflon glass cloth to the bottom of the aluminum tool.

3. Lay up plies 1 to 3, ply T1, plies 4 and 5, ply T2, and plies 6 to 8 per Table 4-2. Preply as required.

4. Apply one ply of porous, Teflon-coated glass cloth over lay up, apply 3 plies of style 7581 glass fabric followed by 1/8-inch rubber overpress. Apply three plies of style 7581 glass fabric as vent. Place two thermocouples in the edge of the laminate and one on the tool. Bag for precompaction.

5. Precompact as follows: Apply a minimum of 24 inches of mercury, heat in an autoclave at 2 to 5F/minute to 160 ± 5F, apply 50 psig autoclave pressure, hold 15 to 20 minutes, and cool under vacuum and pressure to below 100F at a rate not to exceed 5F/minute.

6. Remove bag, vent, overpress, bleeder fabric, and Teflon-coated glass cloth.

7. Lay up ply T3 plies 9 to 11, ply T4, plies 12 to 14, ply T5, and plies 15 to 17 per Table 4-2. Preply as required.

8. Repeat steps 4, 5, and 6.

9. Lay up ply T6, plies 18 to 20, ply T7, plies 21 to 23, ply T8, and plies 24 to 26 per Table 4-2. Preply as required.

10. Repeat steps 4, 5 and 6.

11. Lay up ply T9, plies 27 to 29, ply T10, plies 30 to 32, ply T11, and plies 33 to 35 per Table 4-2. Preply as required.

12. Repeat steps 4, 5, and 6.

13. Lay up ply T12, plies 36 to 38, ply T13, plies 39 to 41, ply T14, and plies 42 to 44 per Table 4-2. Preply as required.

14. Repeat steps 4, 5, and 6.

15. Lay up ply T15, plies 45 to 47, ply T16, plies 48 to 50, ply T17, and plies 51 to 53 per Table 4-2. Preply as required.

16. Repeat steps 4, 5, and 6.

17. Lay up ply T18 plies 54 to 56, ply T19, plies 57 to 59, T-20, and plies 60 to 62 per Table 4-2. Preply as required.

18. Repeat steps 4, 5, and 6.

19. Lay up ply T21 plies 63 to 65, ply T22, plies 66 to 68, ply 23, and plies 69 to 71 per Table 4-2. Preply as required.

20. Repeat steps 4, 5, and 6.

21. Lay up ply T24, plies 72 and 73, ply T25, and plies 74 to 76 per Table 4-2. Preply as required.

22. Apply bleeder system consisting of porous, Teflon-coated glass cloth, one ply of style 120 glass fabric and two plies of style 7581 glass fabric. Apply a 1/8-inch thick rubber overpress followed by three plies of style 1534 glass fabric to serve as a vent. Place two thermocouples in the edge of the laminate and one on the tool. Bag for cure.

23. Cure as follows: Apply a minimum of 24 inches of mercury on the bag at RT, hold for a minimum of 30 minutes, heat the part in autoclave at a rate of 2 to 4F/minute to 250 ± 10F, hold at that temperature for 45 ± 5 minutes, apply 100 psig autoclave pressure in less than 5 minutes, hold an additional 45 ± 5 minutes, heat the part at a rate of 2 to 4F/minute to 350 ± 10F, hold for 120 minutes, and cool the part at a rate not to exceed 5F/minute under vacuum and pressure.

24. Debag and remove part from the tool.

The specimens were cut to size using the same procedure described in Section 4.1.1 with the exception that the feed rate was slowed to 0.5 to 1.0 inch/minute because of the thicker sections. This sawing operation resulted in specimens with an excellent edge finish similar to that obtained previously on half-thickness specimens. No further machining was necessary.

4.2 FRUSTA FABRICATION

The two frusta fabricated represented the forward 11 inches of a full-scale frustum (Figure 2-1).

The bulk graphite tool was designed with removable bulk graphite flange rings that have smaller inside diameters than the ends of the cone tool to which they bolt (Figure 4-3). A wooden cradle was built to support the tool during layup and this allowed easy tool rotation during layup.

Large unidirectional sheets of GY-70/934 were prepared by layup of parallel and butted plies of the 2.75-inch wide unidirectional prepreg tape. The sheets were laid between plies of porous, Teflon-coated glass cloth, placed under a vacuum bag at a minimum pressure of 29 inch of mercury, and held at room temperature for a minimum of 15 minutes. After debagging, gores were cut from the large sheets using predetermined templates as detailed in Table 4-3. Gores were placed into the tool by first removing one layer of the separator film and then laying the gore in at a predetermined location per Table 4-3. Protractors were designed to fit on both front and back of the tool when the flanges were in place. This allowed for accurate placement of the gores.

The tool was designed so that they would produce an 11.0 inch high cone frustum after trimming approximately 0.75 inch from each end. This trimming would remove the more prominent local surface discontinuities of the cones that generally occur near edge dams.

A detailed step-by-step procedure for the fabrication of the cones is as follows:

1. Lay up 76 32 inch x 14 inch sheets of unidirectional GY-70/934 to prepare all gores needed for layup of one cone. Note batch and roll numbers of all prepreg used in layup.

2. Remove flanges from bulk graphite tool. Apply FreKote 33 to tool and bake for one hour at 300F. Repeat three times and reattach flanges and attach protractors to front and back ends of tool.

3. Cut titanium gores from 0.005 -inch thick 6Al-4V titanium foil sufficient for all plies needed for layup of one cone.

4. Prepare titanium

   Cleaning: Immerse in solution of OAKITE-HD126 (106 gm/2.5 gallons of water) at 140 to 180F for 5 to 15 minutes. Rinse with tap water at RT.

   Pickling: Immerse for two minutes maximum in solution of 2.0 to 3.0 fluid ounces/gallon HF and 40 to 50 fluid ounces/gallon HNO_3 at RT. Rinse titanium with tap water. Immerse for 1.5 to 2.5 minutes at RT in a solution of 6.5 to 7.0 ounces/gallon Na_3PO_4, 2.5 to 3.0 ounces/gallon of KF, and 2.2 to 2.5 fluid ounces/gallon of 70% HF. Rinse in tap water and follow with a 15 minute soak in deionized water at 145 to 155F.

   Storage: Place processed titanium between lint free cheesecloth and store at RT until ready for use. Note: All titanium to be handled with lint free white nylon gloves.

5. Lay up plies 1 to 3, ply T1, plies 4 and 5, ply T2, plies 6 and 7, ply T3, and plies 8 and 9 per Table 4-3. Preply after each ply of titanium (Ti) as a minimum.

6. Apply one ply of porous, Teflon-coated glass cloth over layup, apply 3 plies of style 7581 glass fabric, and then a 1/8-inch rubber overpress. Apply three plies of style 7581 glass fabric as vent. Place two thermocouples in the edge of the laminate and one on the tool. Bag for precompaction.

7. Precompact as follows: Apply a minimum of 24 inches of mercury, heat in an autoclave at 2 to 5 F/minute to 160 ± 5F, apply 50 psig autoclave pressure, hold 15 to 20 minutes, and cool under vacuum and pressure to below 100F at a rate not to exceed 5F/minute.

8. Remove bag, vent, overpress, bleeder fabric, and Teflon-coated glass cloth.

9. Lay up ply T4, plies 10 and 11, ply T5, plies 12 and 13, ply T6, plies 14 and 15, ply T7, plies 16 and 17, ply T8, and ply 18 per Table 4-3. Preply after each ply of Ti as a minimum.

10. Repeat steps 6, 7, and 8.

11. Lay up ply 19, ply T9, plies 20 and 21, ply T10 plies 22 and 23, ply T11 plies 24 and 25, ply T12, and plies 26 and 27 per Table 4-3. Preply after each ply of Ti as a minimum.

12. Repeat steps 6, 7, and 8.

13. Lay up ply T13, plies 28 and 29, ply T14, plies 30 to 32, ply T15 plies 33 to 35, ply T16, and ply 36 per Table 4-3. Preply after each ply of Ti as a minimum.

14. Repeat steps 6, 7, and 8.

15. Lay up plies 37 and 38, ply T17, plies 39 to 41, ply T18, plies 42 to 44, ply T19, and ply 45 per Table 4-3. Preply after each ply of Ti as a minimum.

16. Repeat steps 6, 7, and 8.

17. Lay up plies 46 and 47, ply T20, plies 48 and 49, ply T21, plies 50 and 51, ply T22, plies 52 and 53, ply T23, and ply 54 per Table 4-3. Preply after each ply of Ti as a minimum.

18. Repeat steps 6, 7, and 8.

19. Lay up ply 55, ply T24, plies 56 and 57, ply T25, plies 58 and 59, ply T26, plies 60 and 61, ply T27, and plies 62 and 63 per Table 4-3. Preply after each ply of Ti as a minimum.

20. Repeat steps 6, 7, and 8.

21. Lay up ply T28, plies 64 and 65, ply T29, plies 66 and 67, ply T30, plies 68 and 69, ply T31, plies 70 and 71, ply T32, and ply 72 per Table 4-3. Preply after each ply of Ti as a minimum.

22. Repeat steps 6, 7, and 8.

23. Lay up ply 73, ply T33, and plies 74 to 76 per Table 4-3. Preply after each ply of Ti as a minimum.

24. Remove protractors. Apply bleeder system consisting of one ply of porous, Teflon-coated glass separator, one ply of style 120 glass fabric, and six plies of style 7581 glass fabric. Apply a 1/8-inch thick rubber overpress followed by three plies of style 1534 glass fabric to serve as a vent. Place two thermocouples in the edge of the laminate and one on the tool. Bag for cure.

25. Cure as follows: Apply a minimum of 24 inches of mercury on the bag at RT, hold for a minimum of 30 minutes, heat the part in autoclave at a rate of 2 to 4F/minute to 250 ± 10F, hold at that temperature for 45 ± 5 minutes, apply 100 psig autoclave pressure in less than 5 minutes, hold an additional 45 ± 5 minutes, heat the part at a rate of 2 to 4F/minute to 350 ± 10F, hold for 120 minutes, and cool the part at a rate not to exceed 5F/minute under vacuum and pressure.

26. Debag and remove part from tool.

27. Machine frustum to install fasteners and fabricate antenna cutouts.

28. Mask outside of cone frusta in areas not to be bonded. Sand lightly inside and outside of cone at small end where rings are to be bonded. Use Scotchbrite pads for sanding.

29. Solvent clean bond areas with methylethylketone or trichloroethane. Dry for a minimum of 30 minutes prior to bonding.

30. Machined rings shall be etched and bonded to the frustum. The adhesive used shall be Hysol's EA-9309 with a minimum cure of 24 hours at RT between successive ring bonding operations.

31. Inspect dimensions of finished cone per Drawing 48126.

The cones were trimmed by placing them in an American Pacemaker lathe utilizing a round Spauldite (nonmetallic laminate) tapered fixture. The cones were located on the taper of the fixture and clamped to it with four small soft clamps at the small end of the cone. A tool post grinder was set up on the compound of the lathe using a 6-inch diameter by 0.03-inch wide 60 grit diamond plated wheel run at 8,500 sfm using a flood coolant (deionized water). The cone was trimmed by rotating it by hand and moving the cut-off wheel into the workpiece at a rate of several thousandths of an inch per cone revolution. After the large end of the cone was trimmed, four clamps were placed at its outer end and clamped to the cone. The clamps at the small end were then removed and trimming was then accomplished in the same manner as at the large end of the cone. Figure 4-4 illustrates the setup used on the American Pacemaker lathe.

The drilling and countersinking of the cones was accomplished on an Induma vertical milling machine (Figure 4-5). An aluminum tooling plug was used to hold the composite cone in place. Both units were clamped to a rotary table for indexing purposes. The 0.38-inch diameter holes were drilled using cobalt high-speed steel drills run at 120 rpm and 0.0015 inch per revolution feed rate through the graphite/epoxy/titanium laminates. The 100° countersinking operation was also performed with cobalt high-speed steel countersinks run at 80 rpm and hand fed. The large antenna cutouts were machined using high-speed steel spade drills run at 80 rpm and 0.0015 ipr feed rate. These holes were roughed out to within 0.050 inches of finish dimension using this method and then were bored to size with a C-2 tungsten carbide tipped boring bar run at 120 rpm and 0.003 ipr feed rate.

Delaminations were detected in the first frusta in the area where the lathe jaws were in contact with the forward end. A repair was made using Hysol's EA-9412 modified epoxy, capillary adhesive. The end of the frusta was coated with adhesive and placed in a bell jar. The adhesive was allowed to cure for 24 hours at RT under vacuum. Subsequent machining and inspection of that surface indicated that the delamination had been completely repaired.

Table 4-1. Splice Panel Layup Sequence

Ply No.	Orientation
1 (outside)	0
2	0
3	45
4	90
5	135
6	90
7	45
8	0
9	0
10	0
11	135
12	0
13	0
14	0
15	45
16	0
17	0
18	135
19	0
20	0
21	135
22	0
23	0
24	45
25	0
26	0
27	0
28	135
29	0
30	0
31	0
32	45
33	90
34	135
35	90
36	45
37	0
38	0

Table 4-2. Aft Joint Laminate Layup Sequence

Ply No.	Orientation	Ply No.	Orientation
1	0	TA-13	Ti
2	0	39	0
3	45	40	0
TA-1	Ti	41	45
4	90	TA-14	Ti
5	135	42	90
TA-2	Ti	43	135
6	90	44	90
7	45	TA-15	Ti
8	0	45	45
TA-3	Ti	46	0
9	0	47	0
10	0	TA-16	Ti
11	135	48	0
TA-4	Ti	49	135
12	0	50	0
13	0	TA-17	Ti
14	0	51	0
TA-5	Ti	52	0
15	45	53	45
16	0	TA-18	Ti
17	0	54	0
TA-6	Ti	55	0
18	135	56	135
19	0	TA-19	Ti
20	0	57	0
TA-7	Ti	58	0
21	135	59	135
22	0	TA-20	Ti
23	0	60	0
TA-8	Ti	61	0
24	45	62	45
25	0	TA-21	Ti
26	0	63	0
TA-9	Ti	64	0
27	0	65	0
28	135	TA-22	Ti
29	0	66	135
TA-10	Ti	67	0
30	0	68	0
31	0	TA-23	Ti
32	45	69	0
TA-11	Ti	70	45
33	90	71	90
34	135	TA-24	Ti
35	90	72	135
TA-12	Ti	73	90
36	45	TA-25	Ti
37	0	74	45
38	0	75	0
		76	0

Table 4-3. Orientation and Size on Gore Sections

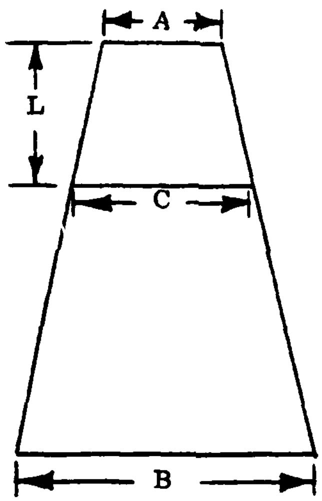
Ply No.	Orientation of Ply	α	Wrap Angle	Diameter D_A	D_B	D_C	Gore Size (see sketch) A	B	C	L
Outside										
1	0	0°	30	7.8451	10.5898	9.515	2.053	2.772		
2	0	15°	30	7.83	10.57		2.051	2.769		
3	45	7°30'	90	7.82	10.56		6.145	8.301		
TF1	-	22°30'	30	7.81		9.485	2.045		2.483	7.6
4	90	5°	90	7.80	10.55		6.130	8.294		
5	135	20°	90	7.79	10.54		6.122	8.286		
TF2	-	12°30'	30	7.78		9.455	2.038		2.475	7.6
6	90	27°30'	90	7.77	10.53		6.106	8.278		
7	45	17°30'	90	7.76	10.52		6.098	8.262		
TF3	-	2°30'	30	7.75		9.425	2.030		2.467	7.6
8	0	25°	30	7.74	10.51		2.027	2.754		
9	0	10°	30	7.73	10.50		2.025	2.751		
TF4	-	0°	30	7.72		9.316	2.022		2.438	7.24
10	0	15°	30	7.71	10.49		2.019	2.749		
11	135	7°30'	90	7.70	10.48		6.051	8.238		
TF5	-	22°30'	30	7.69		9.286	2.014		2.431	7.24
12	0	5°	30	7.68	10.47		2.012	2.743		
13	0	20°	30	7.67	10.46		2.009	2.740		
TF6	-	12°30'	30	7.66		9.256	2.006		2.423	7.24
14	0	27°30'	30	7.65	10.45		2.004	2.738		
15	45	17°30'	90	7.64	10.44		6.004	8.207		
TF7	-	2°30'	30	7.63		9.153	1.999		2.396	6.91
16	0	25°	30	7.62	10.43		1.996	2.731		
17	0	10°	30	7.61	10.42		1.992	2.730		
TF8	-	0°	30	7.60		9.123	1.991		2.388	6.91
18	135	15°	90	7.59	10.41		5.965	8.183		
19	0	7°30'	30	7.58	10.40		1.985	2.725		
TF9	-	22°30'	30	7.57		9.083	1.983		2.378	6.91
20	0	5°	30	7.56	10.39		1.980	2.723		
21	135	20°	90	7.55	10.38		5.933	8.160		
TF10	-	12°30'	30	7.54		8.991	1.975		2.354	6.58
22	0	27°30'	30	7.53	10.37		1.972	2.717		
23	0	17°30'	30	7.52	10.36		1.970	2.715		
TF11	-	2°30'	30	7.51		8.961	1.967		2.345	6.58
24	45	25°	90	7.50	10.35		5.894	8.136		
25	0	10°	30	7.49	10.34		1.962	2.709		
TF12	-	0°	30	7.48		8.931	1.959		2.338	6.58
26	0	15°	30	7.47	10.33		1.957	2.706		
27	0	7°30'	30	7.46	10.32		1.954	2.704		
TF13	-	22°30'	30	7.45		8.901	1.952		2.330	6.58
28	135	5°	90	7.44	10.31		5.847	8.105		
29	0	20°	30	7.43	10.30		1.945	2.699		
TF14	-	12°30'	30	7.42		8.798	1.943		2.303	6.25
30	0	27°30'	30	7.41	10.29		1.940	2.696		
31	0	17°30'	30	7.40	10.28		1.938	2.694		
32	45	2°30'	90	7.39	10.27		5.808	8.074		
TF15	-	25°	30	7.38		8.758	1.933		2.293	6.25
33	90	10°	90	7.37	10.26		5.792	8.066		
34	135	0°	90	7.36	10.25		5.784	8.058		
35	90	15°	90	7.35	10.24		5.776	8.050		

Table 4-3. Orientation and Size on Gore Sections (Cont'd)

				Diameter			Gore Size (see sketch)			
ly No.	Orientation of Ply	α	Wrap Angle	D_A	D_B	D_C	A	B	C	L
utside										
TF16	-	7°30'	30	7.34		8.718	1.923		2.282	6.25
36	45	22°30'	90	7.33	10.23		5.761	8.042		
37	0	5°	30	7.32	10.22		1.917	2.678		
38	0	20°	30	7.31	10.21		1.915	2.675		
TF17	-	12°30'	30	7.30		8.678	1.912		2.272	6.25
39	0	27°30'	30	7.29	10.20		1.909	2.673		
40	0	17°30'	30	7.28	10.19		1.907	2.670		
41	45	2°30'	90	7.27	10.18		5.713	8.003		
TF18	-	25°	30	7.26		8.566	1.902		2.242	5.92
42	90	10°	90	7.25	10.17		5.698	7.995		
43	135	0°	90	7.24	10.16		5.690	7.987		
44	90	15°	90	7.23	10.15		5.682	7.979		
TF19	-	7°30'	30	7.22		8.526	1.891		2.232	5.92
45	45	22°30'	90	7.21	10.14		5.662	7.971		
46	0	5°	30	7.20	10.13		1.885	2.654		
47	0	20°	30	7.19	10.12		1.884	2.652		
TF20	-	12°30'	30	7.18		8.486	1.881		2.222	5.92
48	0	27°30'	30	7.17	10.11		1.878	2.649		
49	135	17°30'	90	7.16	10.10		5.627	7.940		
TF21	-	2°30'	30	7.15		8.456	1.873		2.214	5.92
50	0	25°	30	7.14	10.09		1.870	2.644		
51	0	10°	30	7.13	10.08		1.868	2.641		
TF22	-	0°	30	7.12		8.353	1.865		2.187	5.59
52	0	15°	30	7.11	10.07		1.862	2.639		
53	45	7°30'	90	7.10	10.06		5.580	7.909		
TF23	-	22°30'	30	7.09		8.323	1.857		2.179	5.59
54	0	5°	30	7.08	10.05		1.855	2.633		
55	0	20°	30	7.07	10.04		1.852	2.631		
TF24	-	12°30'	30	7.06		8.293	1.849		2.171	5.59
56	135	27°30'	90	7.05	10.03		5.541	7.885		
57	0	17°30	30	7.04	10.02		1.844	2.625		
TF25	-	2°30'	30	7.03		8.194	1.842		2.145	5.26
58	0	25°	30	7.02	10.01		1.839	2.623		
59	135	10°	90	7.01	10.00		5.509	7.861		
TF26	-	0°	30	7.00		8.164	1.834		2.137	5.26
60	0	15	30	6.99	9.99		1.831	2.618		
61	0	7°30'	30	6.98	9.98		1.828	2.615		
TF27	-	22°30'	30	6.97		8.134	1.826		2.129	5.26
62	45	5°	90	6.96	9.97		5.470	7.838		
63	0	20°	30	6.95	9.96		1.821	2.610		
TF28	-	12°30'	30	6.94		8.028	1.818		2.102	4.93
64	0	27°30'	30	6.93	9.95		1.816	2.607		
65	0	17°30'	30	6.92	9.94		1.813	2.605		
TF29	-	12°30'	30	6.91		7.998	1.810		2.094	4.93
66	135	25°	90	6.90	9.93		5.423	7.806		
67	0	10°	30	6.89	9.92		1.805	2.599		
TF30	-	0°	30	6.88		7.968	1.802		2.086	4.93
68	0	15°	30	6.87	9.91		1.799	2.596		
69	0	7°30'	30	6.86	9.90		1.797	2.594		

Table 4-3. Orientation and Size on Gore Sections (Cont'd)

Ply No.	Orientation of Ply	α	Wrap Angle	Diameter D_A	D_B	D_C	Gore Size (see sketch) A	B	C	L
Outside										
TF31	-	22°30'	30	6.85		7.8668	1.795		2.059	4.60
70	45	5°	90	6.84	9.89		5.376	7.775		
71	90	20°	90	6.83	9.88		5.368	7.767		
TF32	-	12°30'	30	6.82		7.8368	1.787		2.051	4.60
72	135	27°30'	90	6.81	9.87		5.352	7.759		
73	90	17°20'	90	6.80	9.86		5.345	7.751		
TF33	-	2°30'	30	6.79		7.8068	1.779		2.044	4.60
74	45	25°	90	6.78	9.85		5.329	2.581		
75	0	10°	30	6.77	9.84		1.773	2.579		
76	0	0°	30	6.7651	9.8398		1.747	2.576		
Inside										



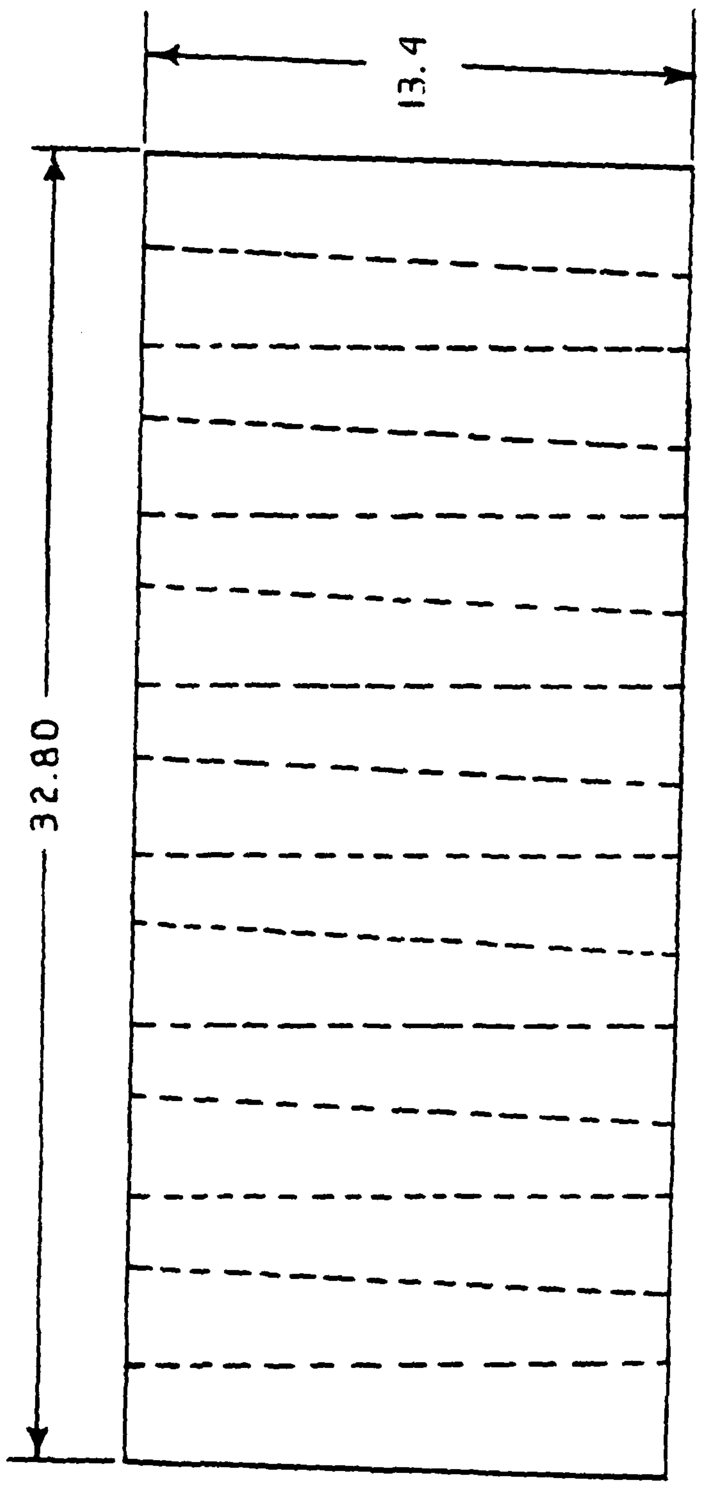
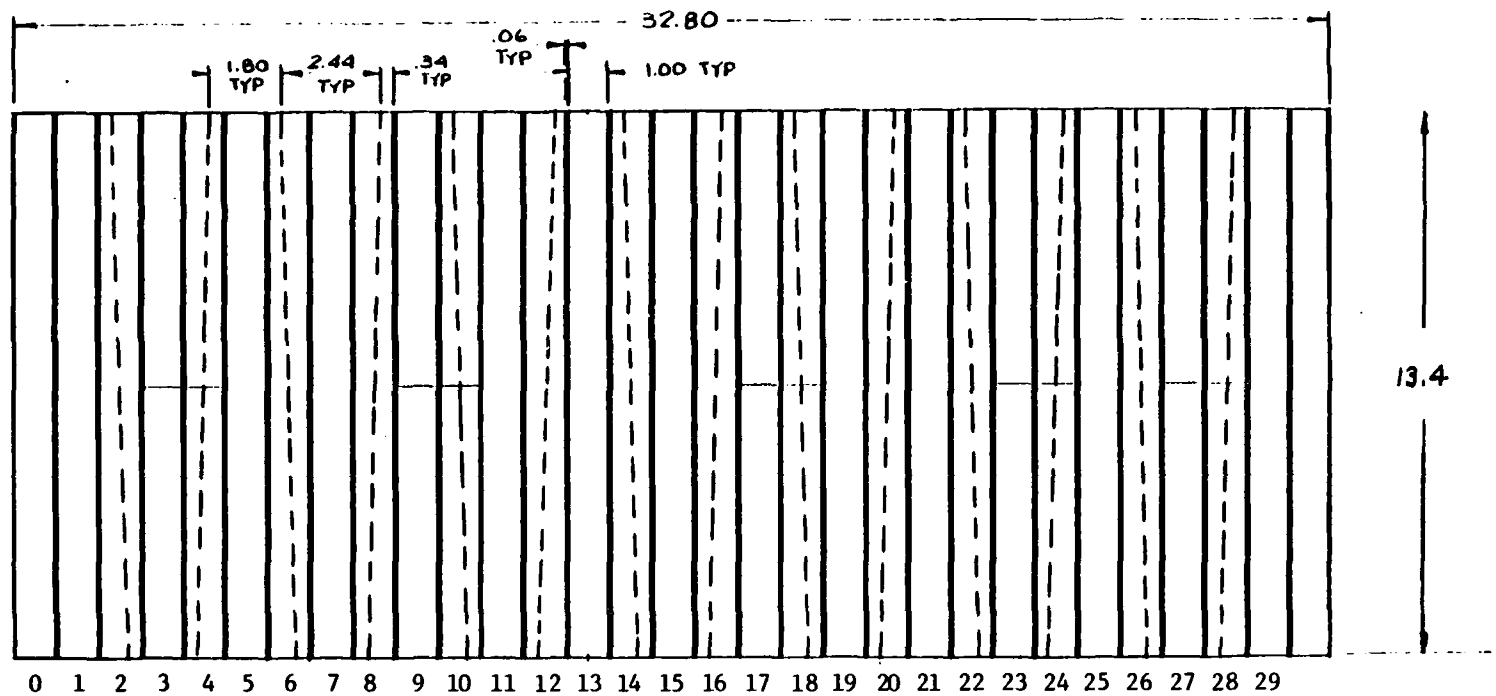


Figure 4-1. Splice and Control Panel



Specimen No.
of specimens
in Table 6.1 and 6.2

Figure 4-2. Cutting Plan for Splice and Control Specimens

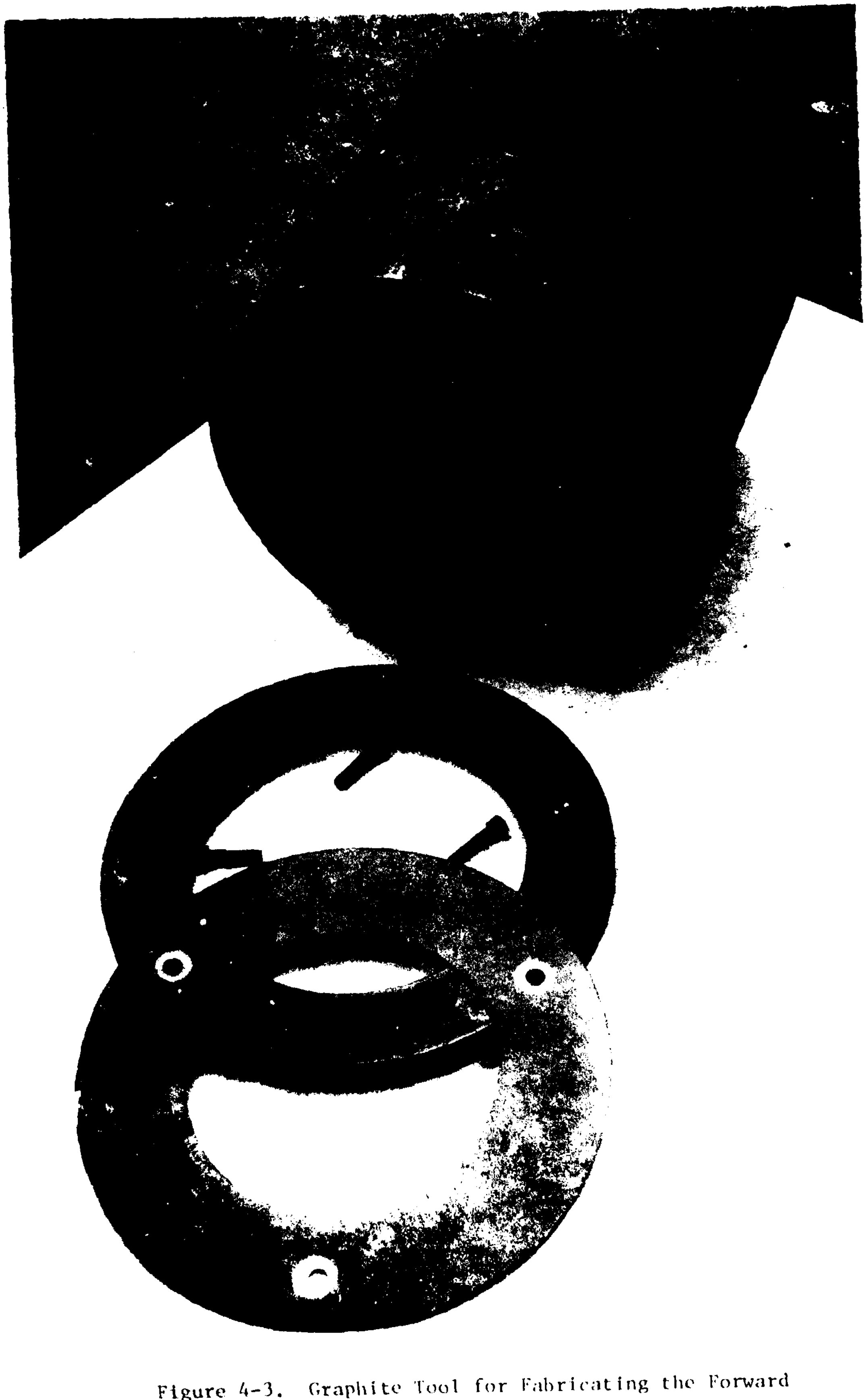


Figure 4-3. Graphite Tool for Fabricating the Forward End of a Full-Scale Frustum

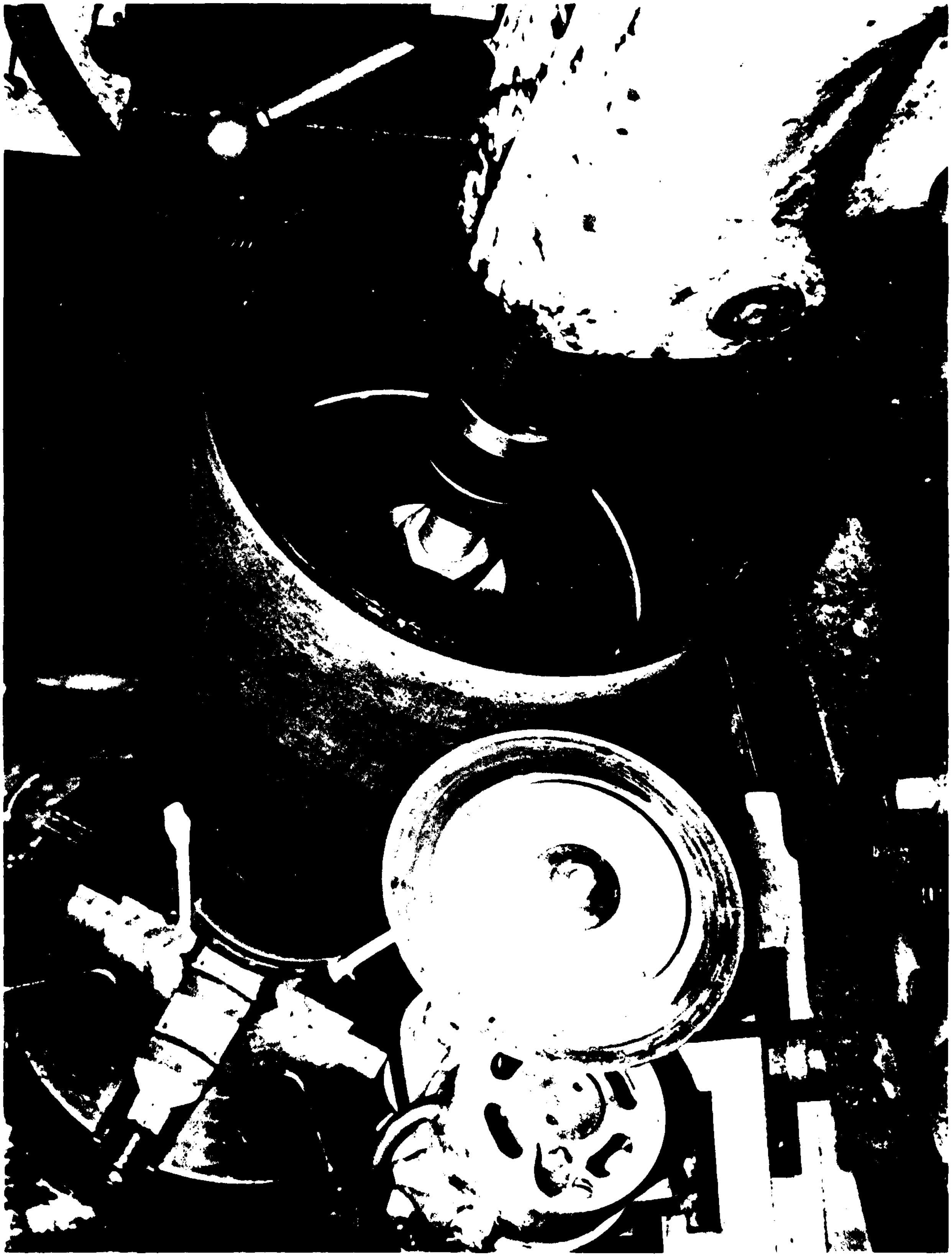


Figure 4-4. End Trimming Operation of Frustum (Photo No. CVD800458)

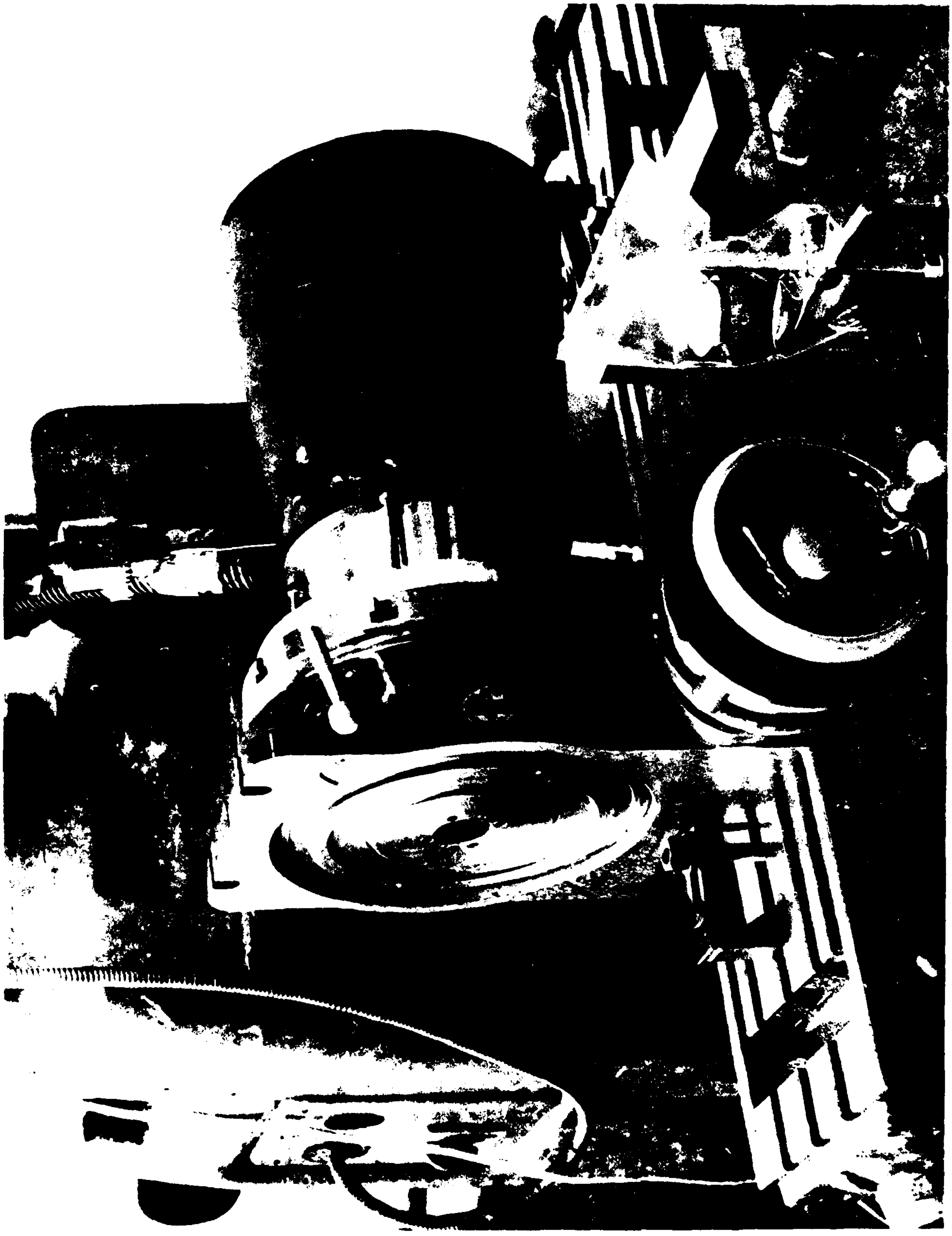


Figure 4-5. Drilling and Reaming Operations of Frustum (Photo No. [illegible]800460)

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SECTION 5

TEST PROCEDURES

5.1 LAMINATE TESTS

Two types of laminate coupon tests were run on this program. These were tension and compression tests of specimens made from a panel prepresenting half the thickness of the full-scale frustum.

5.1.1 Tensile Tests

Eighteen tensile specimens were cut from the laminate panel described in Section 4.1.1 and shown in Figure 4-2. All were tested in the same fashion. Fiberglass doublers 2.5-inches long were bonded to the specimens at their ends. Back-to-back strain gages were bonded to each specimen at the midpoint. FAE-25-12S0 strain gages from BLH were used. The adhesives used were Eastman's 910 cyanoacrylate adhesive for the ambient temperature tests and Micro-Measurement's M Bond 600 for the elevated temperature tests. Tests were run in a universal test machine, and the specimens incrementally loaded. Load and strain were recorded at each increment. The data were subsequently plotted as load-strain curves, and the modulus of elasticity was calculated from this data. Elevated temperature tests were conducted in an environmental chamber installed in the test machine. Temperature was controlled by a thermocouple attached to the test specimen.

5.1.2 Compression Tests

Twenty compression specimens were cut from the laminate panel. They were potted into end blocks to prevent brooming failures. Back-to-back strain gages were also used for these specimens. A specimen in the test apparatus is shown in Figure 5-1. Side supports on this fixture prevent premature buckling. The strength values calculated from these data are ultimate compression strengths. (Reference 5).

Tests were run in a universal test machine and were incrementally loaded. The load and corresponding strain were recorded on the digital strain indicator/ recorder (Figure 5-2). Elevated temperature tests were conducted in an environmental chamber installed in the test machine. Temperature was controlled by a thermocouple attached to the test specimen.

5.2 FLAT JOINT TESTS

Two flat graphite/epoxy joint panels containing interleaved titanium foil and simulating the forward and aft joints were prepared as described in Section 4. Nine specimens were machined from each of the panels. These were bolted to pieces of high strength steel simulating an interstage ring. The steel was offset as shown in Figure 5-3. The load is carried around the steel and introduced into the specimen at the bolts. The first specimen was tested without the potted end cap. This specimen failed by brooming of the end, and subsequently the specimens were potted as shown in Figure 5-3.

Tests were conducted on a Universal test machine. The environmental chamber was used in this machine for the elevated temperature tests. Temperature was controlled by a thermocouple attached to the test specimen. A load-deflection curve was prepared for each test. For these tests, loading was uniformly applied at a crosshead rate of 0.01 inches/minute.

5.3 FRUSTA TESTS

5.3.1 Equipment Ring Tests

The two large-size frusta (LS-1 and LS-2, see Table 1-1), furnished by AMMRC from previous contracts (Reference 3 and 4) were shortened as shown in Figure 5-4. This was done to prevent a crippling mode of failure during test and to allow access to the top of the graphite/epoxy equipment ring. Each frustum was cut to a total height of five inches, i.e., one inch above and one inch below the equipment ring. The bottom end was potted into a grooved aluminum plate to prevent brooming of the end. A 1/4-inch thick sheet of aluminum was cut to size so that it could rest on top of the equipment ring. Thicker sheets of smaller diameter were then placed onto this ring to serve as loading pads.

The tests were conducted at ambient temperature in a Universal test machine. Deflection versus load was measured by using a deflectometer attached to the machine recording system. The curve was examined to find any discontinuities indicating failure.

5.3.2 Forward Frusta Tests

The two frusta discussed in Section 4.2 were tested in combined loading as shown schematically in Figure 5-5. In order to accomplish this a steel loading piece simulating the splice ring at station 27.5 was fabricated. The bolt bearing thickness varied from 0.25 to 0.5 inches as it would for the actual ring. This steel piece was bolted to the test section with 21 of the 125-ksi bolts discussed in Section 3.3. The aft portion of each frustum was held in an aluminum ring as previously described (References 1 and 4). The ring for forward frustum No. 1 (FF No. 1) was 2-inches long and had a square cross section. The ring for the second frustum (FF No. 2) was 3-inches long and had a tapered section to reduce the stress concentration. This is shown in Figure 5-6.

Six single element and six rosette strain gages were bonded to each frustum near the bolts to obtain load introduction data. The location of these gages is shown in Figure 5-7. The single element gages were FAE 25-12S0 gages from BLH while the rosettes were FAER-25R-12S0 gages from BLH. All the gages were installed with Eastman's 910 cyanoacrylate adhesive. The system was set to prevent lead wire desensitization.

A frustum installed in the test fixture is shown in Figures 5-8 and 5-9. The loads were induced by simultaneously acting hydraulic cyclinders. This is accomplished by using a pressure valving system.

The system was set at zero and the load increased in increments of 20% of the design limit load (DLL) as shown in Table 5-1 up to 100% of DLL. After reaching 100% DLL the increments were reduced to 10% of DLL until failure. The loads (4) and strains (24) were read and recorded at each increment. Failure loads were noted and plots of strains versus these loads were prepared. The maximum strains were calculated to determine the failure mode.

Table 5-1. Design Limit Loads at Station 27.5 (Forward End of Guidance and Control Section).

P (axial compression)	=	29,700 lb
M (moment)	=	282,000 in-lb
V (shear)	=	21,000 lb

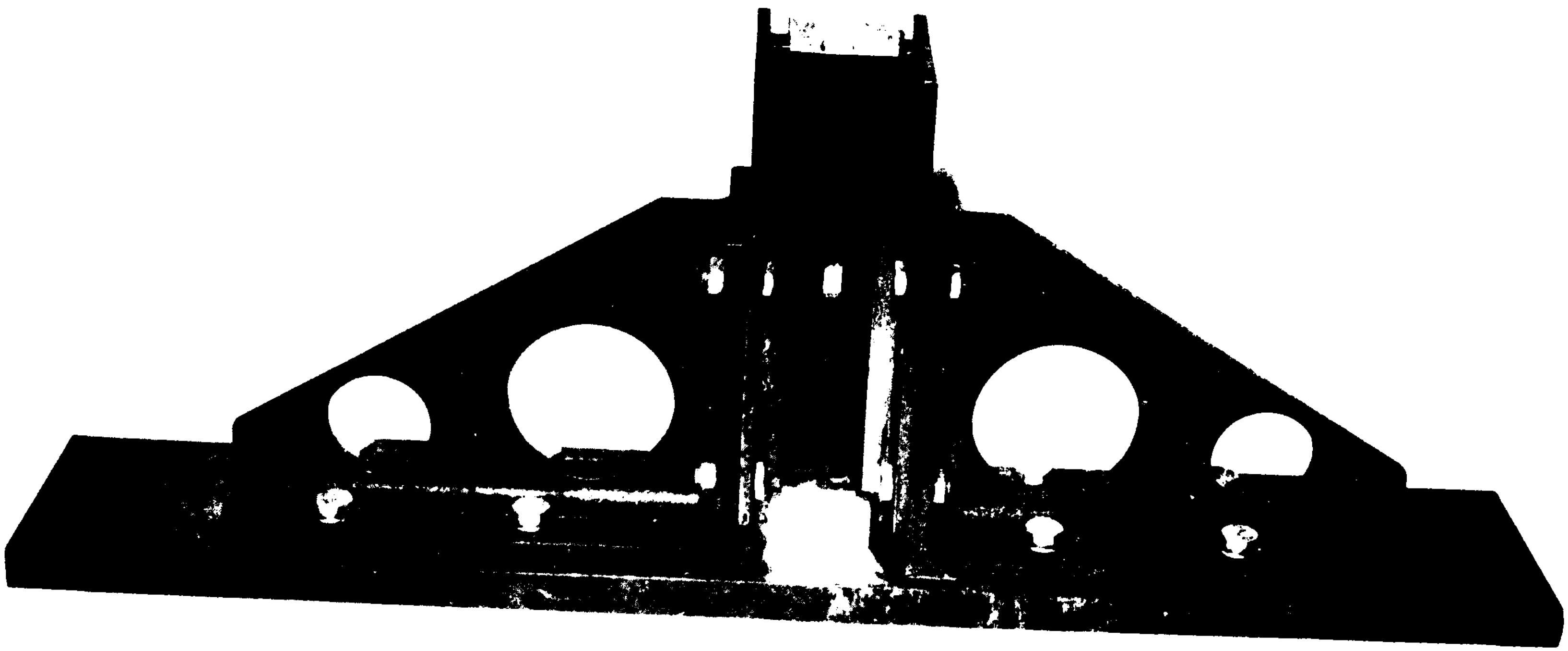

Figure 5-1. Compression Test Fixture and Specimen

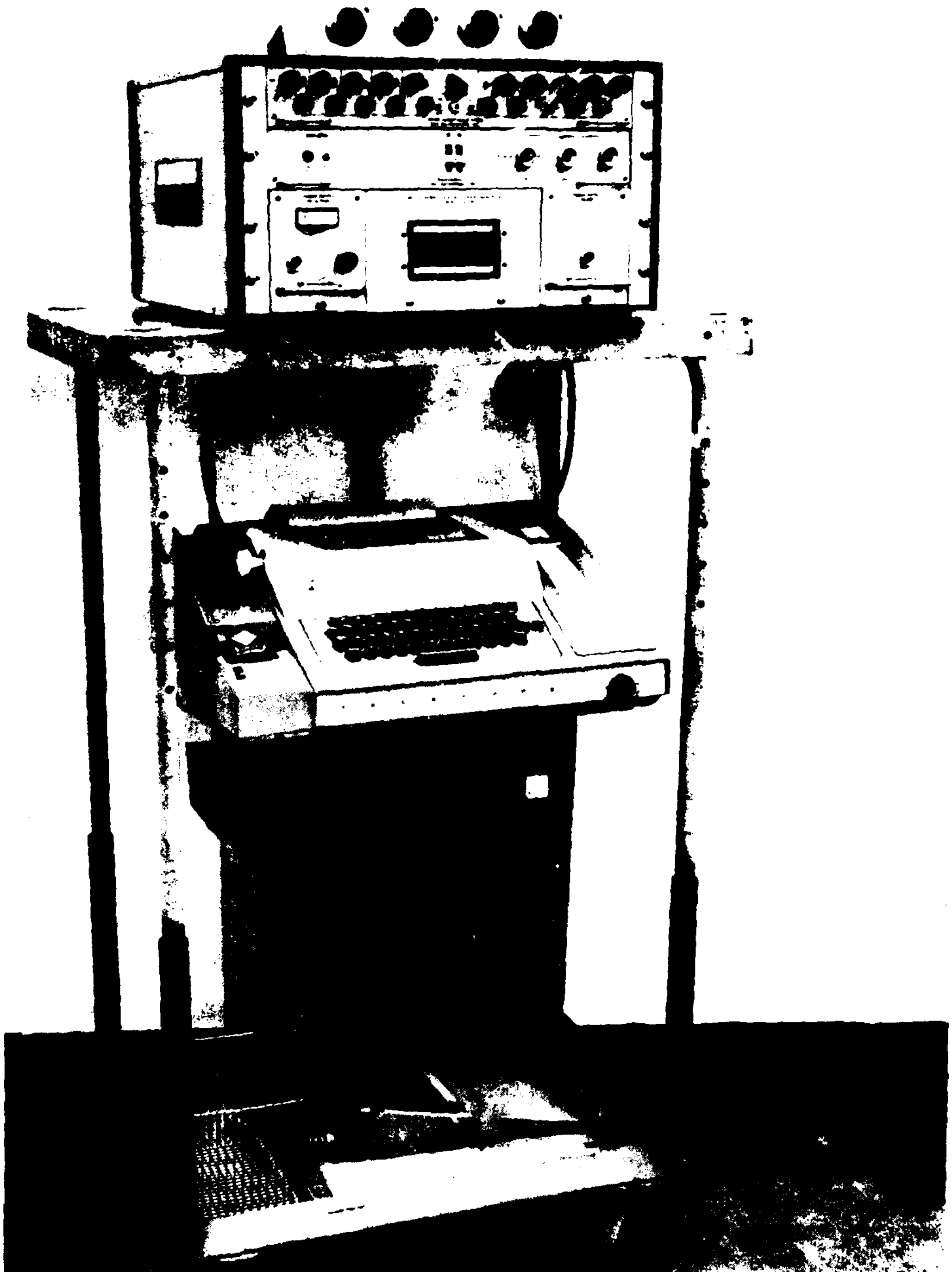

Figure 5-2. Digital Strain Indicator/Recorder Used to Measure & Record Strain

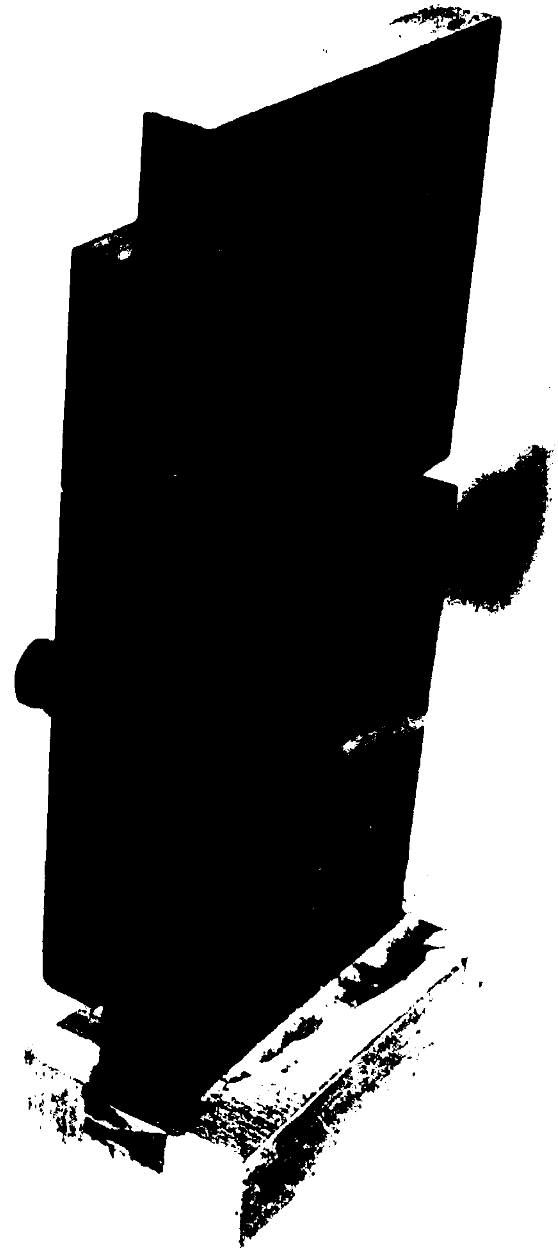

Figure 5-3. Joint Test Specimen With Steel Loading Fixture. Specimen Potted to Prevent End Brooming.

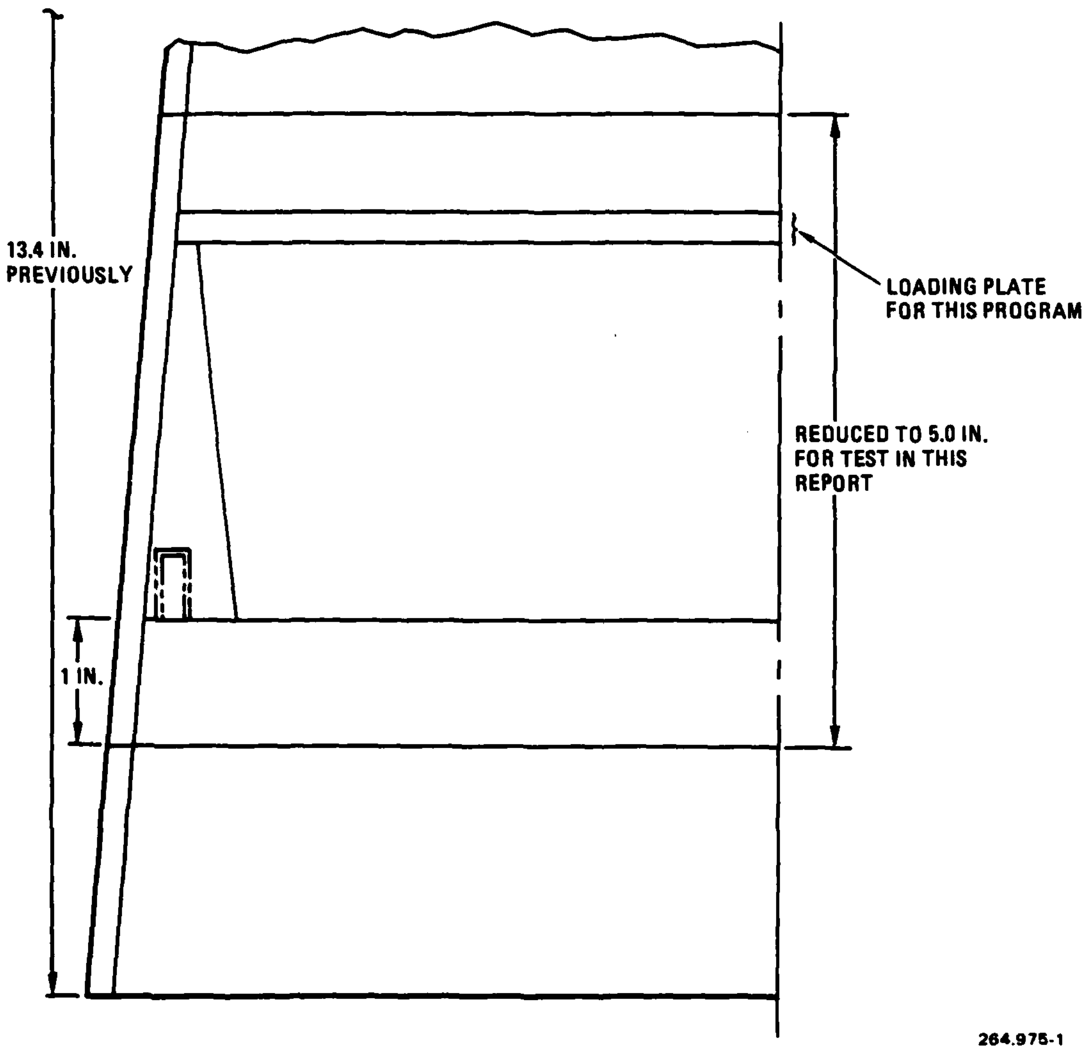

Figure 5-4. Large Size Frusta Used in Equipment Ring Tests.

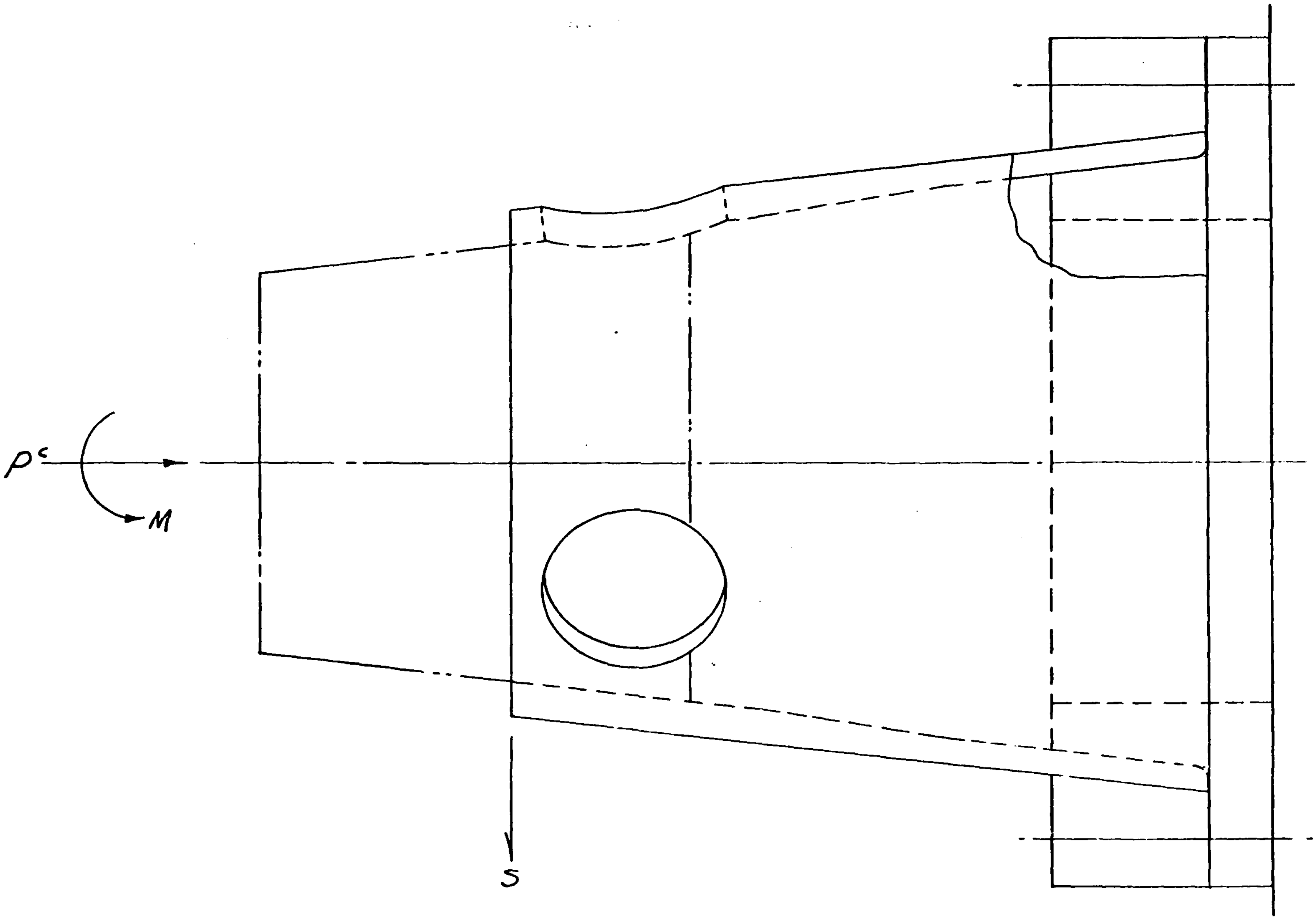

Figure 5-5. Fwd End Joint Test Setup Concept

Figure 5-6. Forward Frustum No. 2 (FF#2) With Loading Ring and Fixture.

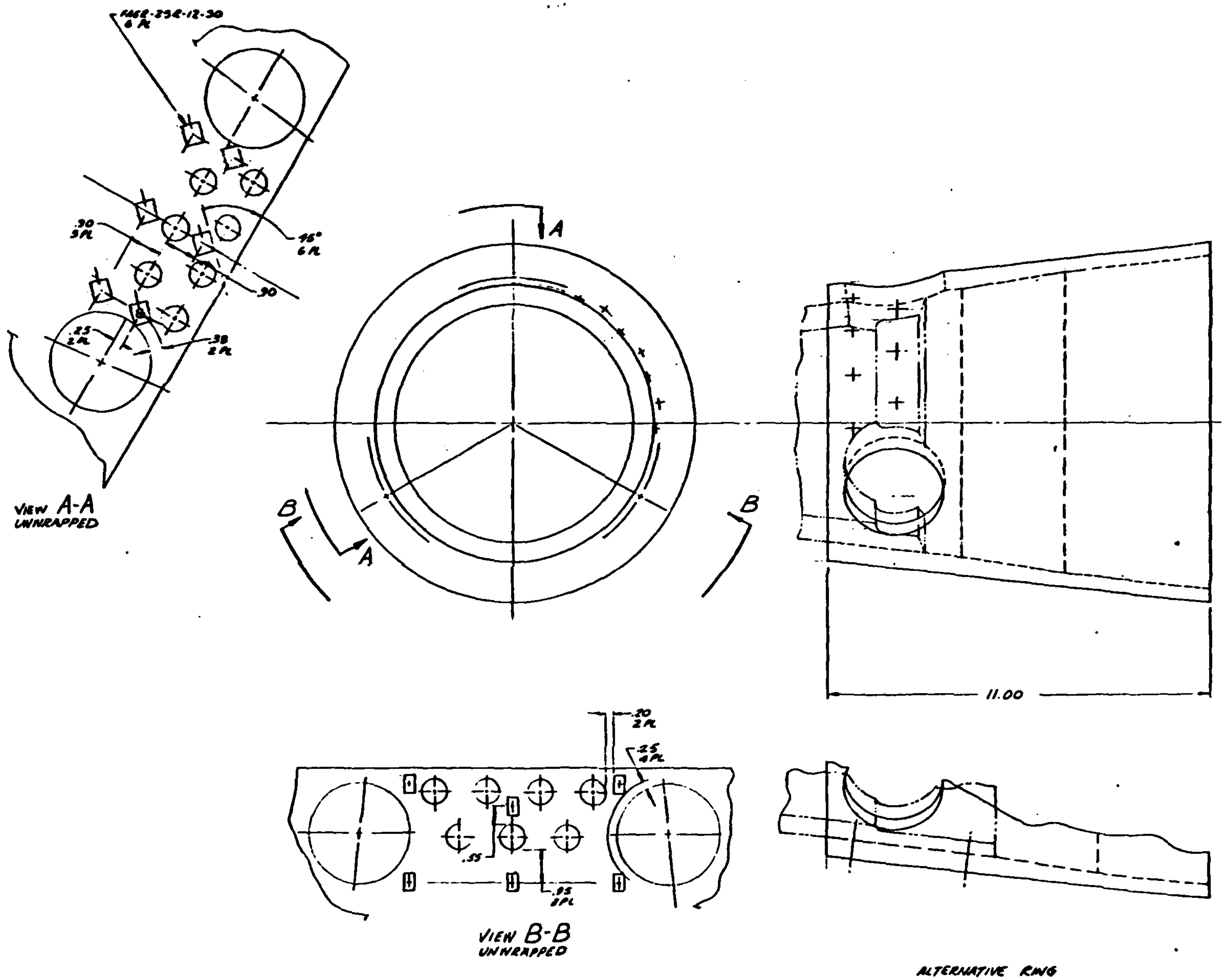

Figure 5-7. **Forward End Frusta**

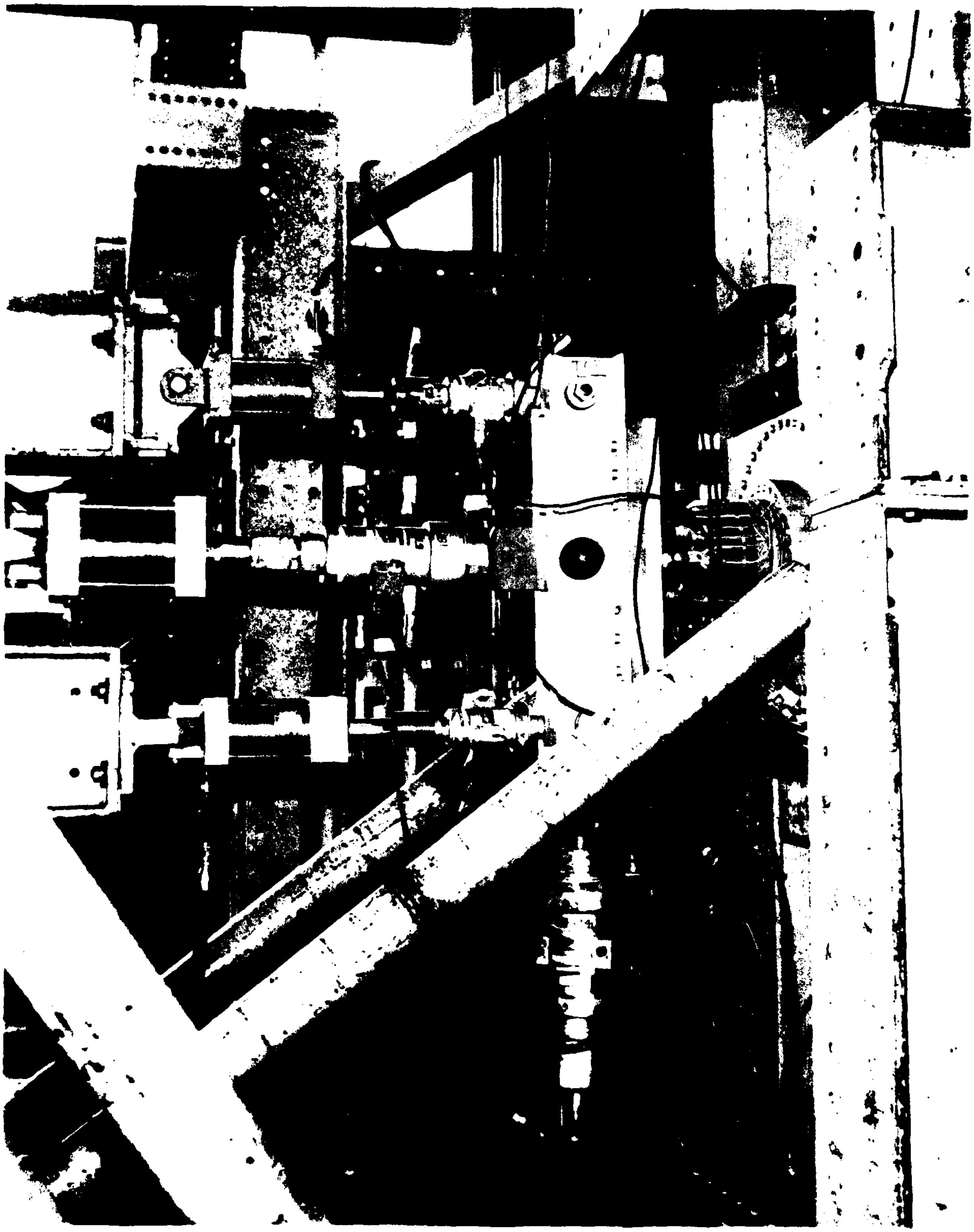

Figure 5-8 Frustum Ready for Test

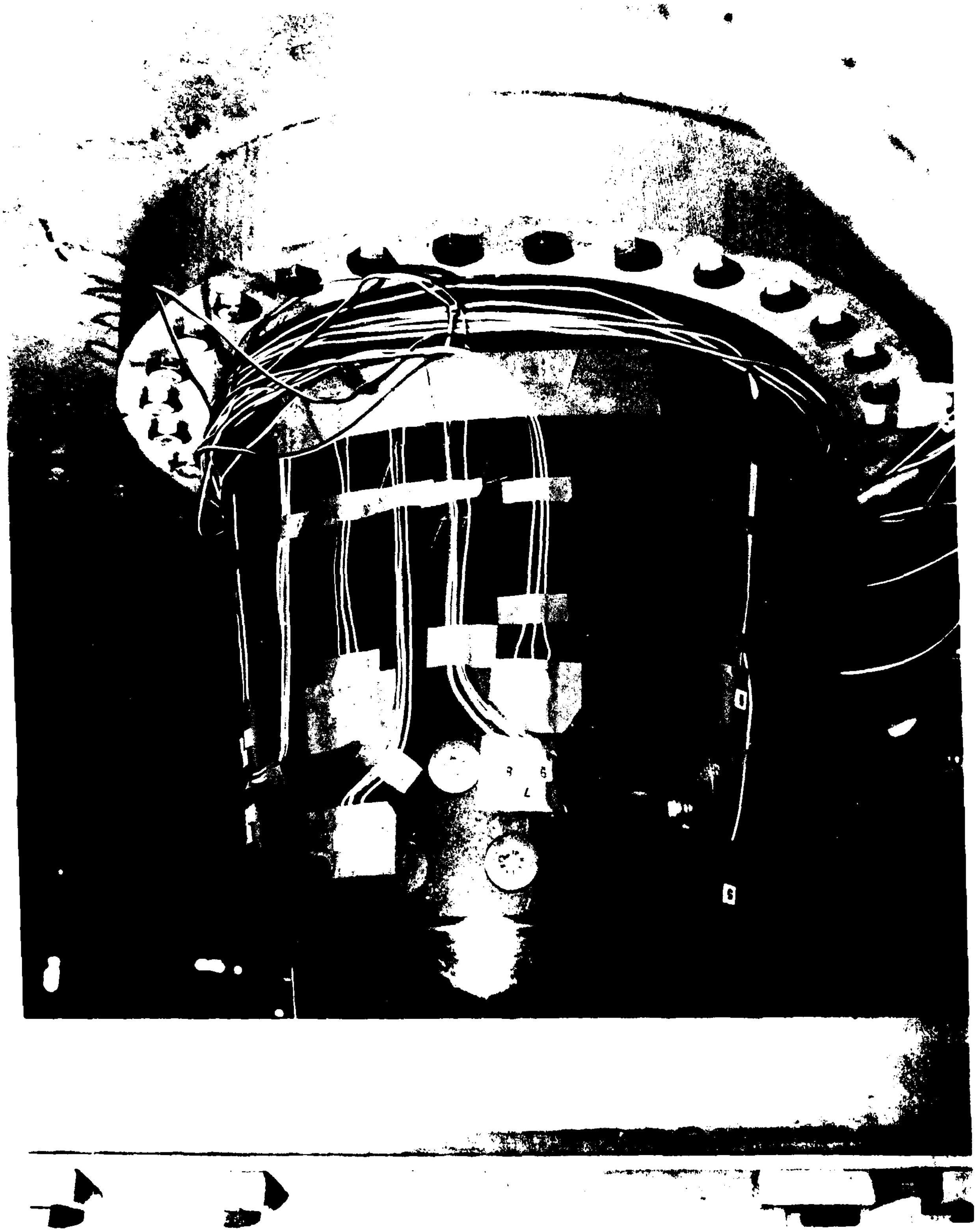

Figure 5-9. Close up of Full Thickness Forward Frustum

SECTION 6

DISCUSSION OF TEST RESULTS

6.1 LAMINATE TESTS

Tables 6-1 and 6-2 summarize the test results of the 18 tensile and 20 compression tests. These results are plotted in Figures 6-1 to 6-3. Review of these data leads to the following observations. First, tensile strength of specimens containing discontinuous 0^{o} fibers (spliced specimens) are approximately the same as those made with only continuous fibers. This differs from the results reported by Pettit, et al (Reference 6) on testing of high-strength graphite/epoxy composites. The significance of the data reported here is that there would be no measurable effect on frusta strength as a result of using the gore splicing technique. Compression strength data reported here for the spliced specimens are slightly higher than for the specimens with continuous fibers. These differences are small, within the scatter one expects for GY-70/934, and is not considered statistically significant. A large scatter is inherent in very high modulus composites. The materials have a very small strain capability. Therefore any small flaws resulting from fabrication of the laminate or specimens machined from the laminate will lead to a strain or stress concentration and localized failure.

The size and distribution of these flaws greatly influence the failure load, and therefore this results in a large scatter of failure loads. In tension, the flaws tend to open and propagate during test, while in compression the flaws tend to seal. Therefore, one would expect greater scatter in tension than in compression. This correlates with the test dates.

Average compression strength at room temperature is very close to the average strength obtained on testing of sub-scale frusta (Reference 4). Elevated temperature specimen testing gave approximately the same results in compression and slightly higher values in tension than those obtained at ambient. It is therefore obvious that short time elevated temperature exposure such as that expected in some sections of the ATI would not affect the integrity of the vehicle.

Modulus of elasticity values for the tensile and compression test specimens have been calculated and are tabulated in Tables 6-1 and 6-2. These data are plotted in Figure 6-3. It is apparent that temperature has little affect on modulus of elasticity up to 325F. The average for all 38 modulus data points is 26.6 ksi. This is extremely close to the analytically determined value (Reference 1) of 26.7 ksi. This proves that there is excellent translation of the basic fiber and resin properties to composite properties. Based on this data, the full-scale design (Reference 4) which is 0.38 inches thick will exceed the frequency requirement by 10 percent. This 10 percent is the safety factor traditionally used to account for frequency losses at joints.

6.2 JOINT TESTS

Results of the eighteen joint tests are given in Table 6-3. Data are plotted as a function of temperature in Figure 6-4. The aft joint is designed to carry 15,165 lb/in, and each bolt is designed to carry 11,400 lb (Reference 4). Aft joint specimens were 3.54 inches wide and were designed to carry 53,700 lb. Average load at failure exceeds this requirement. The actual frusta joint should carry an even larger load because it is circular at the base and the overturning moment in the flat test specimen will not be present in the frusta. This indicates that the full-scale design (Reference 4) is adequate and can be expected to carry 1.5 times the design limit load which is the requirement.

The forward joint is designed by the bolt loads. The maximum bolt load is 13,600 lb/bolt. For a four-bolt specimen, the specimen should carry 54,400 lb. The ambient temperature specimens did carry a load in excess of this requirement. Again the actual frusta can be expected to be adequate.

No elevated temperature strength requirements for the joints have been defined, but the load carrying ability of the joints is only slightly reduced at elevated temperatures up to 325F. Since the loading on the frustum decreases rapidly in the latter phases of flight (i.e., as the frustum is heated), this again ensures the adequacy of the design.

6.3 FRUSTA TESTS

6.3.1 Frusta With Equipment Rings

The objective of these tests was to obtain failure strength for the bond joint between the frustum and ring. Two previously tested frusta were used for this purpose. The previous tests (Reference 4) had pulled out the helicoils but had not caused failure of the bond joints. The results of the latest tests are given in Table 6-4. The failure data from the previous tests are also included for comparison. Since the previous tests had proven the adequacy of the joint, the new tests were run to determine the extent of the margin of safety. This would be important in resizing the ring if the margin were very large. It would also be needed if the loads of the ring changed which again would result in a redesign. These data have been used in the finite element model discussed in detail in the Section 7.

The strength of the bonded joint between the frustum and the equipment ring, as tested was at least 7% higher than the strength of the helicoils. However, margin of safety previously reported (Reference 4) was 19%. This is close enough to an optimum design, and therefore doesn't warrant redesign. The actual margin of safety for a full-scale equipment ring sized to fail the bond joint is 100% (see Section 7.1.6).

We cannot take full advantage of this capacity of the bonded joint because there is a need to have a mechanical joint (bolted) to allow the replacement of the equipment package. This need to replace or repair the equipment package is the reason that the helicoils were originally installed into the bonded ring. The helicoil joint, has the lower strength, and hence is the critical design factor.

6.3.2 Forward Frusta Tests

Both forward frusta components exceed the design limit load given in Table 5-1. The actual failure loads are given in Table 6-5. The loading of FF #1 reached 130 percent of DLL, and failed at the test fixture ring rather than in the area near the antenna cutout. There was no failure of bolts or of the laminate (either bearing or shear) in the area near the antenna cutout. The failed frustum is shown in Figure 6-5. This indicated that a frustum having a fixture ring that produced a lower stress concentration should result in a higher test value. The fixture ring for FF #2 was designed to reduce that stress concentration. FF #2 failed at 159 percent of DLL. Catastrophic failure was avoided by suddenly releasing the load when a noise was heard during testing and consequently the frusta is still intact. The failure occurred at two positions. The bond between the fixture ring and the frusta failed and there is a shear failure of the basic joint. This latter failure was one that was experienced during the joint specimen tests and is typified by a specimen failure shown in Figure 6-5. The failure of the frustum did not progress to the point that it was readily visible and hence is not shown.

The strain data from the gages near the antenna cutout show no anomalies. The highest measured strain from the plots made from the load versus strain data (Section 5.3.2) on FF #1 was 974 microstrain and a calculated maximum shear strain of 1530 microstrain. The highest measured strain on FF #2 was 1344 microstrain and a calculated maximum shear strain of 1520 microstrain. These values are all lower than the strain anticipated to cause failure. Since the gages were not at the failure location, it would be reasonable that they did not reach failure strains.

Two important insights were gained from the frusta testing. First, the full thickness section of the frusta can be fabricated and will carry the required loads (1.5 x DLL). Second, while the frustum with a redesigned fixture ring met the requirements, it did not greatly exceed the load values. This is expected in an optimized design. Excessive margins really mean extra weight. By meeting the modulus and strength requirement both with small margins, the tailoring ability of the material has been utilized.

TABLE 6-1. TENSION TEST RESULTS

Specimen No.	Temperature	Strength, ksi	Modulus, msi
		Continuous 0° Filaments	
1	Ambient	55.1	-
5		34.5	26.3
13		43.1	25.9
21		26.9	24.5
		39.9	25.6
7	225F	54.5	26.0
15		40.5	27.4
25		55.0	28.8
		50.0	27.4
11	325F	52.0	26.2
19		48.8	24.0
29		55.4	27.4
		52.0	25.8
		Discontinuous 0° Filaments	
2	Ambient	34.7	26.9
12		37.0	25.6
20		50.7	28.5
30		41.9	-
		41.1	26.9
6	225F	47.3	24.6
14		47.6	-
22		49.3	24.5
		47.9	24.6
8	325F	50.2	29.2
16		53.6	26.8
26		44.7	24.4
		49.5	26.8

TABLE 6-2. COMPRESSION TEST RESULTS

Specimen No.	Temperature	Strength, ksi	Modulus, msi
		Continuous 0° Filaments	
3A	Ambient	29.4	27.2
9B		41.1	25.1
23A		41.3	25.8
27B		33.7	27.0
		36.4	26.3
3B	225F	45.5	27.7
17A		34.0	27.5
23B		27.7	26.9
		35.7	27.4
9A	325F	36.2	26.9
17B		42.3	28.4
27A		42.1	29.7
		40.2	28.3
		Discontinuous 0° Filaments	
4A	Ambient	45.0	27.5
10B		48.4	26.0
24A		44.7	26.8
28B		46.7	25.0
		46.2	26.3
4B	225F	41.9	26.3
18A		37.6	27.2
24B		39.6	23.0
		39.7	25.5
10A	325F	46.1	28.9
18B		46.9	29.6
28A		40.7	27.4
		44.5	28.6

TABLE 6-3. JOINT SPECIMEN TEST RESULTS

Panel	Specimen	Temp.		Strength, Lb
Aft Joint	AJ-1	Amb.		51,700
	AJ-9			53,800
	AJ-5			57,300
			Ave.	54,200
	AJ-2	225F		48,400
	AJ-6			48,500
	AJ-7			47,700
			Ave.	48,200
	AJ-3	325F		44,000
	AJ-4			48,000
	AJ-8			47,200
				46,400
Forward Joint	FJ-1	Amb.		42,300+
	FJ-5			56,200
	FJ-9			57,200
			Ave.	56,700
	FJ-2	225F		52,400
	FJ-6			52,700
	FJ-7			51,800
			Ave.	52,300
	FJ-3	325F		51,000
	FJ-4			51,000
	FJ-8			50,400
			Ave.	50,800

+Failed by end brooming, not a joint failure

Table 6-4. Summary of Equipment Ring Tests

Cone	Equipment Ring Material	Results	Failure
LS-2*	Graphite/Epoxy	Broke at 69,000 lb+	Pulled out 1/4-in Helicoils
LS-1*	Graphite/Epoxy	Broke at 49,300 lb+	Pulled out 3/16-in Helicoils
LS-2**	Graphite/Epoxy	Retest Broke at 73,800 lb	Bond & Interface Failure
LS-1**	Graphite/Epoxy	Retest Broke at 103,200 lb	Shear of Ring Material

+Test loads for LS-1 and LS-2

Test Number	Temperature	Loading	Loads for LS-1	Loads for LS-2
1	Ambient	Cone and Equipment Ring	P_F = 129,500	P_F = 64,750
			P_R = 12,600	P_R = 6,300
2	Ambient	Equipment Ring	P_R = 12,600	P_R = 12,600
3	+325	Equipment Ring	P_e = 10,080	P_e = 10,080
4	Ambient	Equipment Ring	To Failure	To Failure

*Tested previously as noted in Table 1-1

**Retests during this contract

TABLE 6-5. FORWARD FRUSTA TEST RESULTS

Identification	Size			
Forward Frustum #1	Full thickness, full size forward section	axial load shear load moment	- 38,600 lb - 366,600 in-lb - 27,300 lb 130% DLL	shear of graphite epoxy at fixture end. No damage near forward end.
Forward Frustum #2	"	axial load shear load moment	- 47,200 lb - 448,300 in-lb - 33,400 lb 159% DLL	shear of graphite epoxy at fixture end & shear of graphite/epoxy at antenna cut-outs.

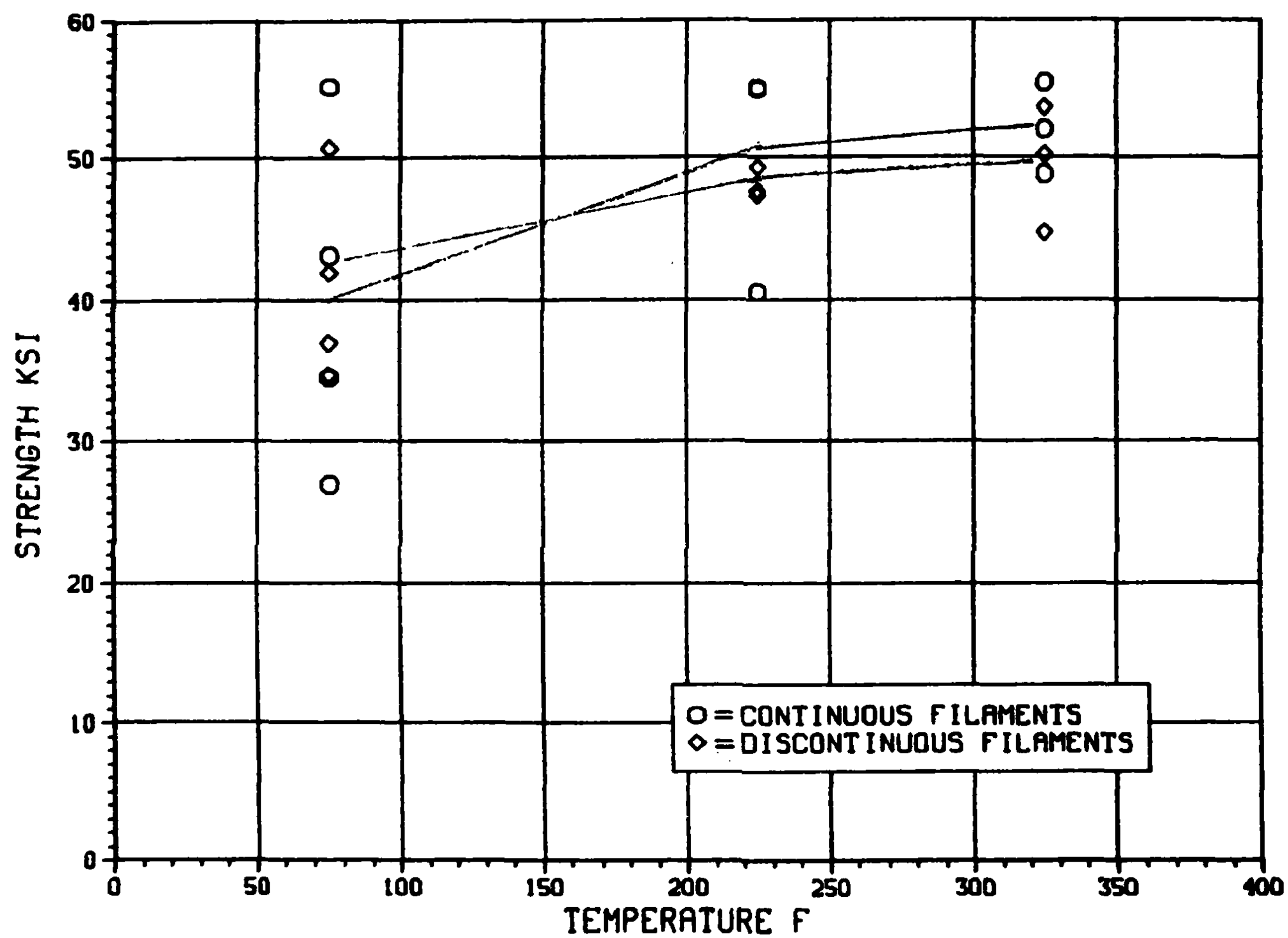

Figure 6-1. Tensile Strength Versus Temperature for Laminate Tests.

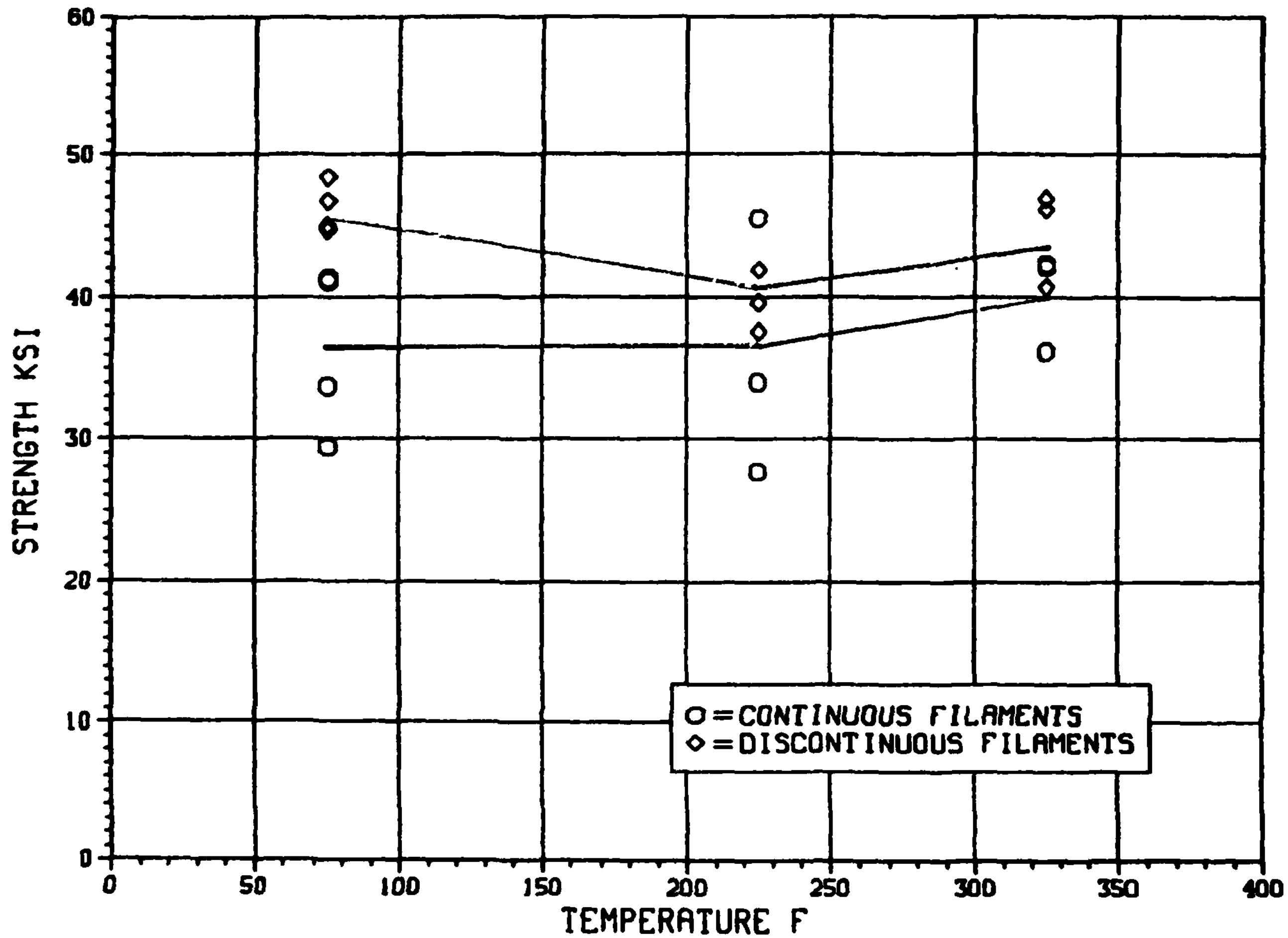

Figure 6-2. Compression Strength Versus Temperature for Laminate Tests.

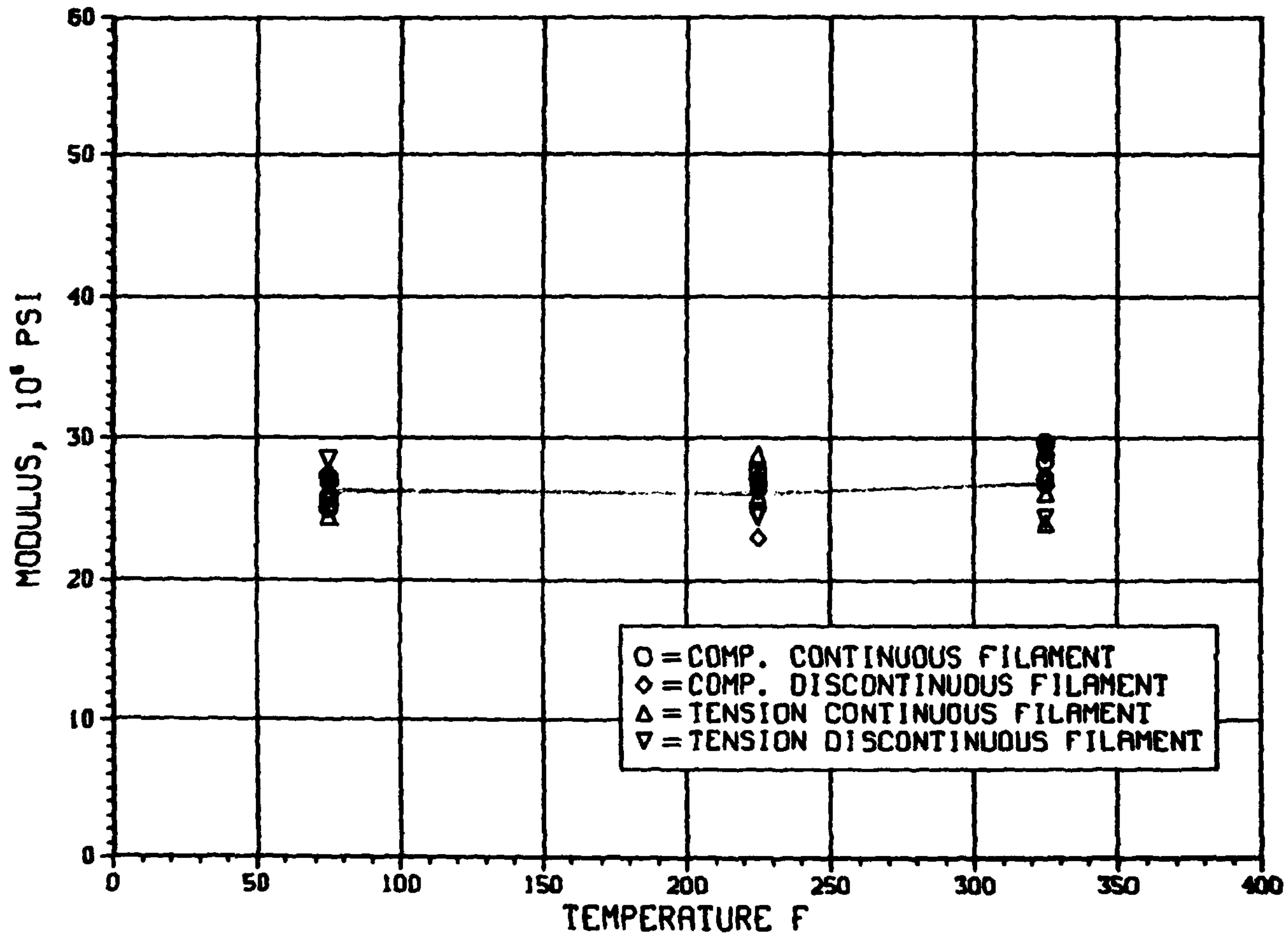

Figure 6-3. Modulus Values Versus Temperature for Laminate Tests

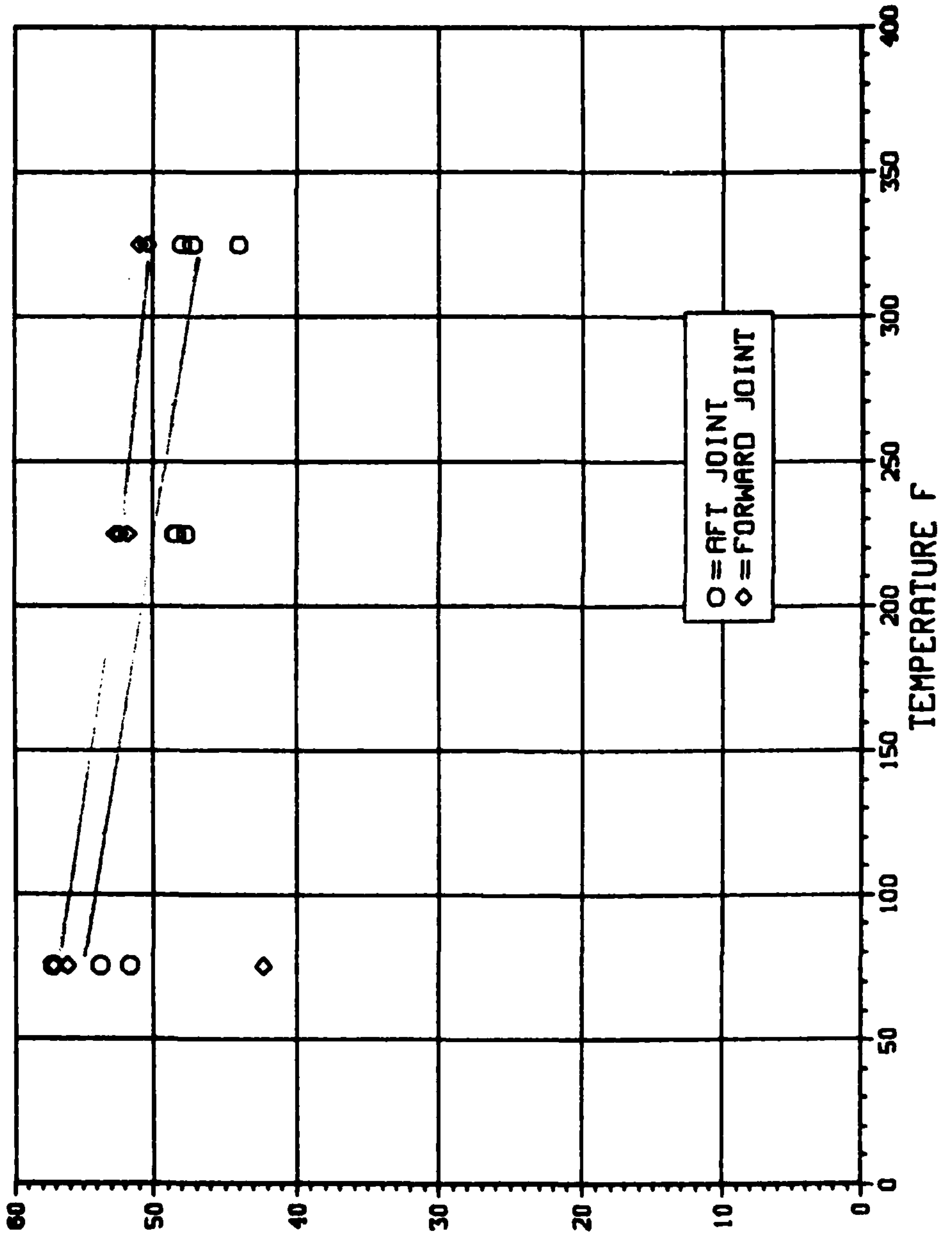

Figure 6-4 Joint Specimen Load Versus Temperature

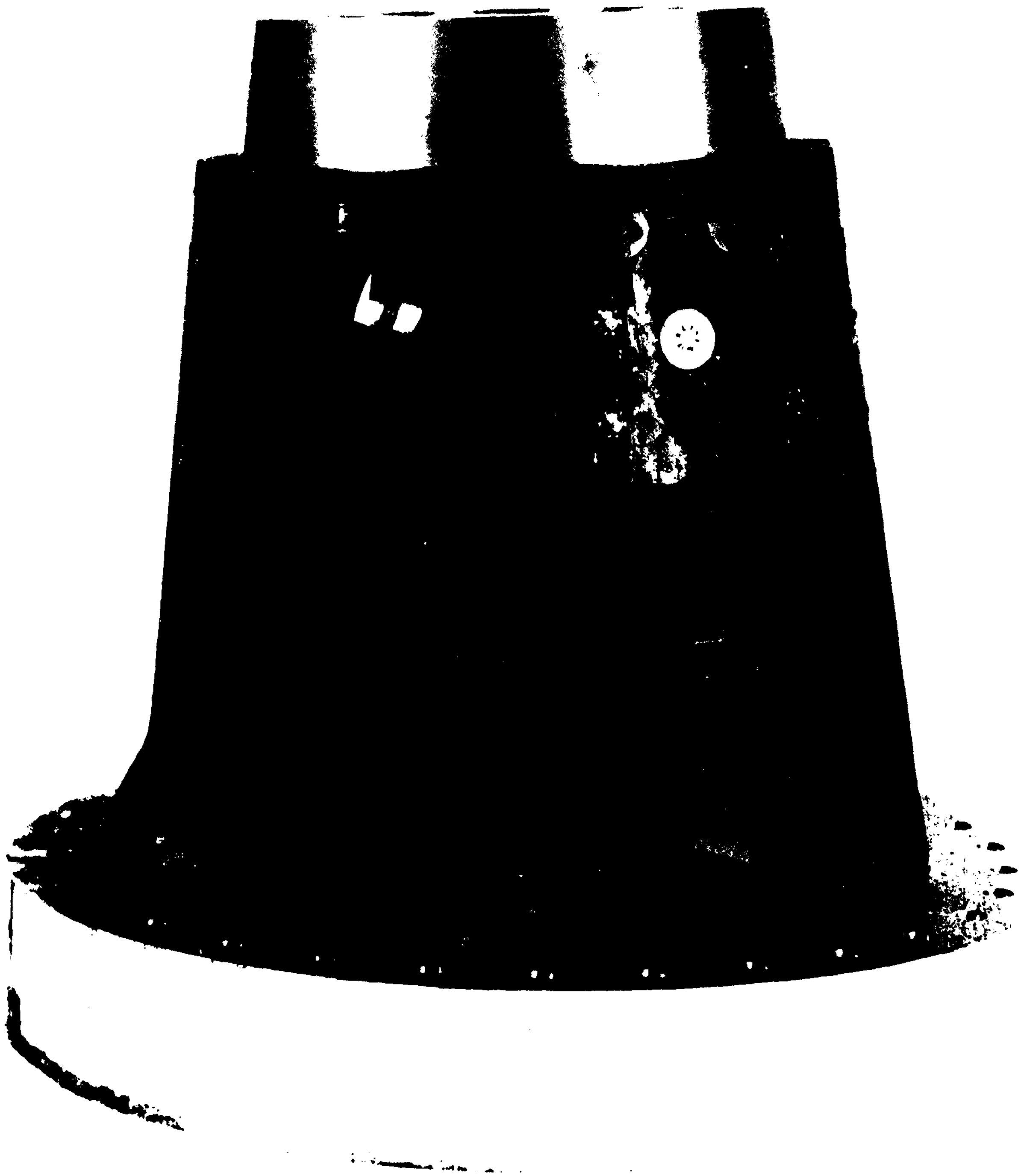

Figure 6-5. Failed forward frustum #1. Failure was at the support ring.

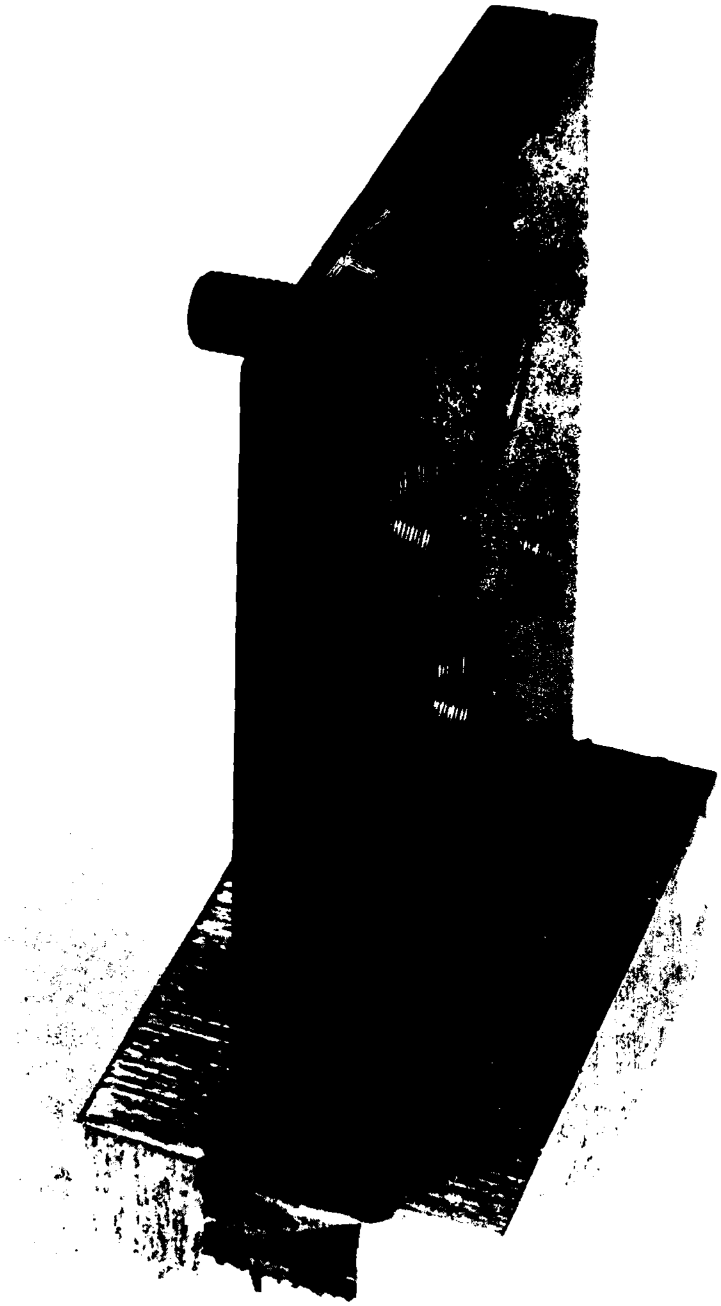

Figure 6-6. Shear failure of joint test specimen.

SECTION 7

ANALYSIS

7.1 FINITE ELEMENT STUDY OF EQUIPMENT RING TO FRUSTUM BOND

A finite element model of a "large size" graphite/epoxy frustum (see Table 2-1) containing an internally bonded equipment ring was developed to provide a better understanding of the stress distribution in the joint. This "large scale" frustum had previously been tested axially (Reference 3) and was retested as described in Section 5.3. It has resulted in significantly higher load carrying capability than predicted by analysis.

The "large size" frustum was a close approximation to the diameter of a full-scale ATI guidance and control section at the equipment ring station. The ring was made of pseudoisotropic T-300/934 while the frustum was made of crossplied GY-70/934. Table 7-1 lists the material property inputs for the ring and frustum composite configurations. The adhesive used in bonding the equipment ring to the inner wall of the frustum was Hysol's EA-934 modified epoxy. Bondline thickness was controlled by incorporation of 4-mil wire shims in the joing (Reference 3).

Table 7.1 Material Properties

Property*	T-300/934 Ring	GY-70/934 Frusta
E11	7.93 msi	26.12 msi
E22	1.65 msi	1.09 msi
E33	7.93 msi	8.10 msi
ν12	0.310	0.381
ν13	0.306	0.358
ν23	0.306	0.308
G_{12}	0.562 msi	0.825 msi

*See Figure 7-1 for directions

7.1.1 Finite Element Model

An axisymmetric finite element model was constructed using element sizes equal to the bondline thickness in the areas of maximum anticipated stress. Outside these high stress areas, the element sizes were incrementally increased while maintaining aspect ratios between 1 and 2. The model was run using the SOLID SAP structural analysis program. The model consisted of: 3492 nodes, 3499 2D elements, and 134 spring elements.

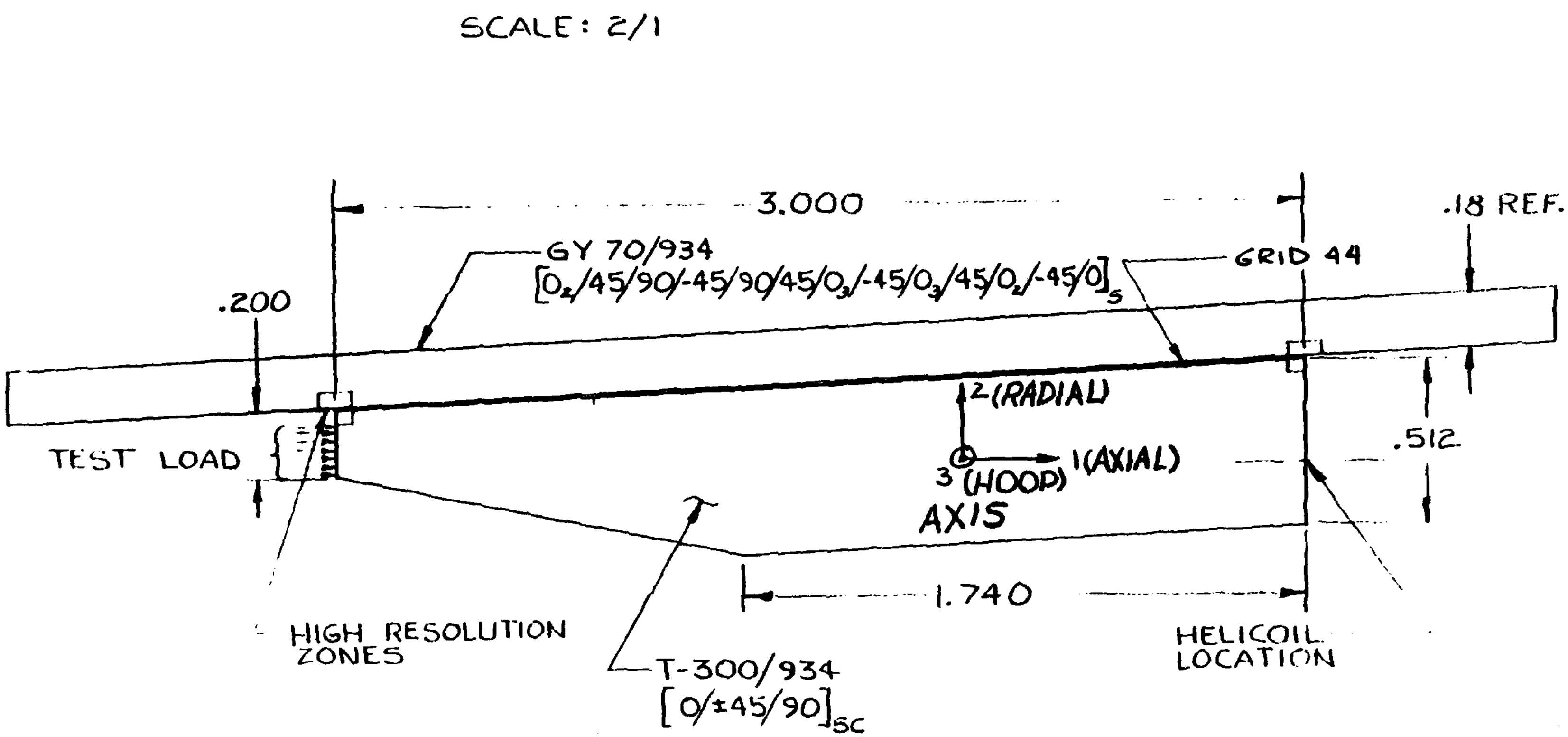

Figure 7-1. Finite Element Model

Figure 7-1 illustrates the model. Because there are a large number of elements in the model, they would not be discernible if one graphic display was used. Therefore the ones in the vicinity of the anticipated stress concentrations were enlarged. Figure 7-2 illustrates typical high resolution grid.

7.1.2 External Loads

The "large size" test frustum was initially loaded through helicoil inserts located in the aft end of the ring (Reference 3 and 4). Due to strength limitations of the helicoils, it was impossible to cause failure of the structure by this manner of loading because the helicoils failed first. The "large size" test frustum was then loaded from the opposite end of the ring in a compression fixture as described in section 5.3.1. This resulted in a bondline failure at 73,800 pounds, which is an average shear stress of 813 psi (see Table 6-4).

The finite element model was analyzed at three load conditions. The first load case (LC1) consisted of an axial load of 73,800 pounds applied in a manner similar to the actual test conditions experienced by the test frustum. The second load condition (LC2) consisted of a unit load of 1,000 pounds per inch applied identically to load case one. The third load case (LC3) was a unit load identical to load case two, applied at the helicoil locations located on the aft end of the ring.

7.1.3 Adhesive Modeling

The adhesive bond between the frustum and ring was modeled as a series of springs. Each adjoining element of the frustum and ring were joined by two springs, one in the radial direction and one in the axial direction. The spring constants were determined using the following procedure:

$$K_N = AE/e$$

$$K_T = AG/e$$

where

K_N = Normal spring constant

K_T = Tangential spring constant

A = Bond line surface area = Rd

e = Thickness of the adhesive

also: d = $\ell / \cos\theta$ where ℓ is the element length used in the finite element model and θ is the half angle of the frusta. See Figure 7-3

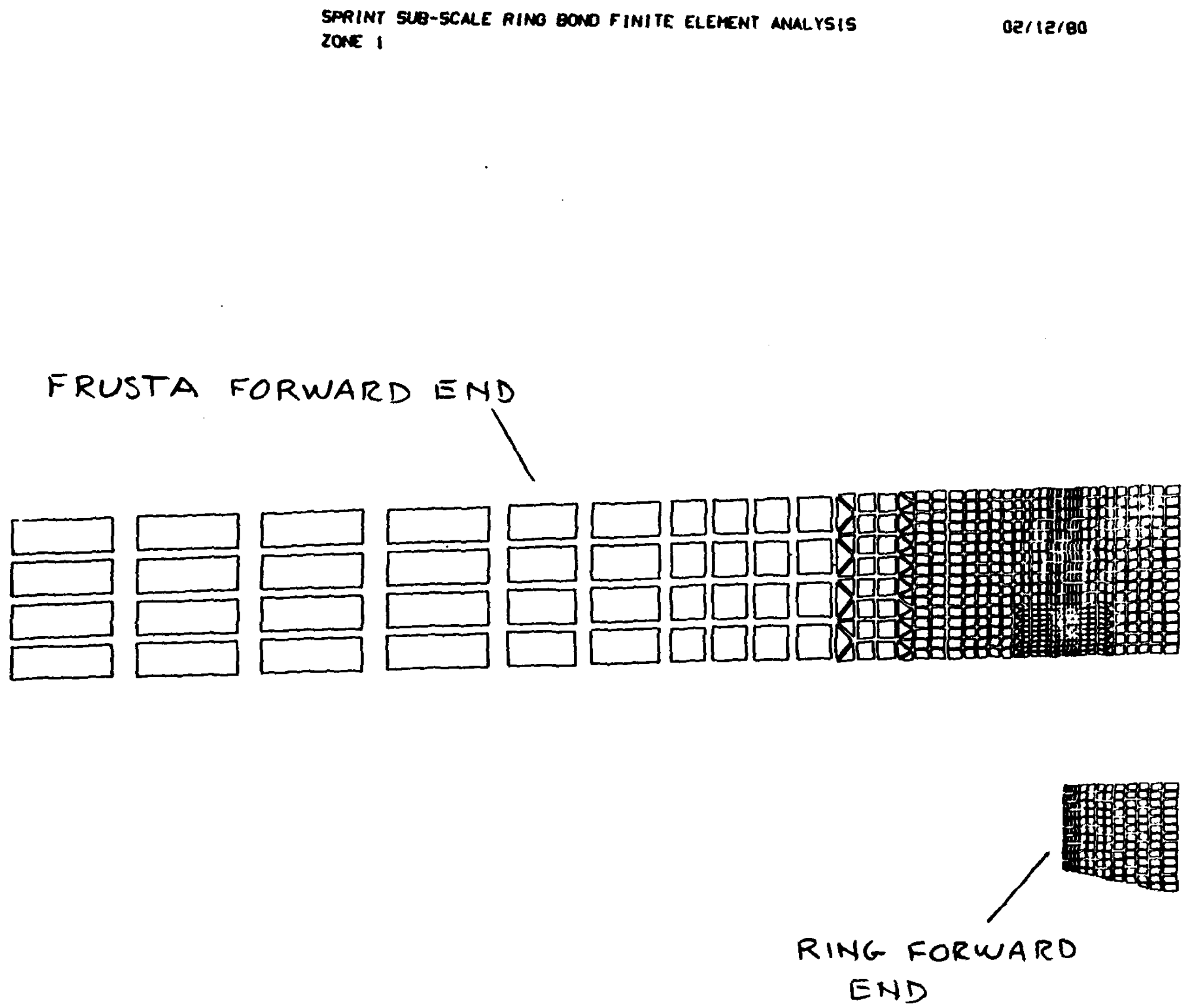

Figure 7.2. Portion of Finite Element Model

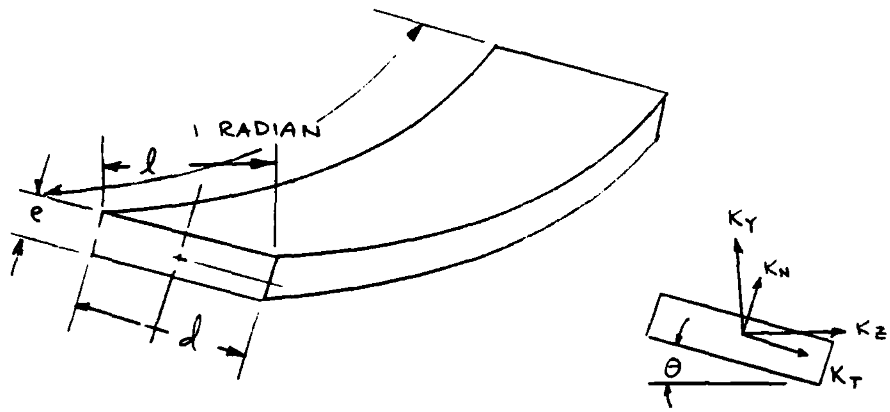

Figure 7-3 Adhesive Element

Converting these spring constants into the Y-Z coordinates of the finite element model result in the following equations:

$$K_z = K_T \cos\theta + K_N \sin\theta$$

$$K_y = K_T \sin\theta + K_N \cos\theta$$

where θ is the angle of the bond line relative to the Z axis of the finite element model.

Rewriting these equations gives the following:

$$K_z = \frac{\ell R}{e}[G + E\tan\theta]$$

$$K_y = \frac{\ell R}{e}[E + G\tan\theta]$$

The adhesive used was EA-934. The values for the elastic modulus and shear modulus are shown in Table 7-2 (Reference 7).

Table 7-2

Modulus	Elastic Range	Plastic Range
E	768,000 psi	590,000 psi
G	279,000 psi	220,000 psi

The angle of the bondline to the Z axis was 4° 40' and the bondline thickness "e" was 0.004 in. Thus the equations can be reduced to:

$$\left.\begin{aligned} K_z &= 8.542 \times 10^7\, \ell R \\ K_y &= 1.977 \times 10^8\, \ell R \end{aligned}\right\} \text{elastic range}$$

$$\left.\begin{aligned} K_z &= 6.704 \times 10^7\, \ell R \\ K_y &= 1.520 \times 10^8\, \ell R \end{aligned}\right\} \text{plastic range}$$

The transition from elastic to plastic was made at grid 44 of the model which is in the region where stresses are beginning to peak. The grid 44 location is shown in Figure 7-1.

7.1.4 Analysis of Finite Element Results

Three computer runs were made using the finite element model. The first run utilized the elastic characteristics of the adhesive throughout the length of the bondline. The second and third runs substituted the adhesive's plastic characteristics beginning at grid 44. The third run also changed the frustum wall thickness from 0.180 to 0.380 in. In each of these runs, three load cases were analyzed as discussed in the Section 7.1.1. The following conclusions resulted from a review of the data.

1. Effects of adhesive characteristics: A comparison of the results of runs 1 and 2 showed that using the plastic characteristics of the adhesive in the high stress regions of the bonded joint had a relatively small effect on the shear stresses developed in the joint. The peak shear stress was reduced from 10,755 psi to 10,513 psi for a reduction of 2.25%. This reduction resulted in a slight increase in shear stress throughout the elastic portion of the adhesive bond, approximately 0.5% or less.

   The peak tensile stress was reduced from 9,475 psi to 9,374 psi for a reduction of 1.07%. The elastic portion of the bondline generally experienced slight increases in the tensile stresses or reductions in compressive stresses except for the extreme forward end which experienced a slight increase in compressive stress.

2. Effects of wall thickness: A comparison of the results of runs 2 and 3 showed that increasing the wall thickness of the frustum had a significant effect on the peak shear stress generated in the bondline. Changing the wall thickness from 0.180 to 0.380 inches produced a reduction from 4,160 psi to 2,724 psi for a 34% reduction in the peak shear stress. This can be seen in Figure 7-4 which compares shear stress distribution along the bondline for the two wall thicknesses. The stresses shown are a result of load case 2. As can be seen in Figure 7-4, the shearing stress is slightly better distributed along the bondline in the thicker walled model. Figure 7-5 illustrates the tensile stress distribution along the bondline. There is

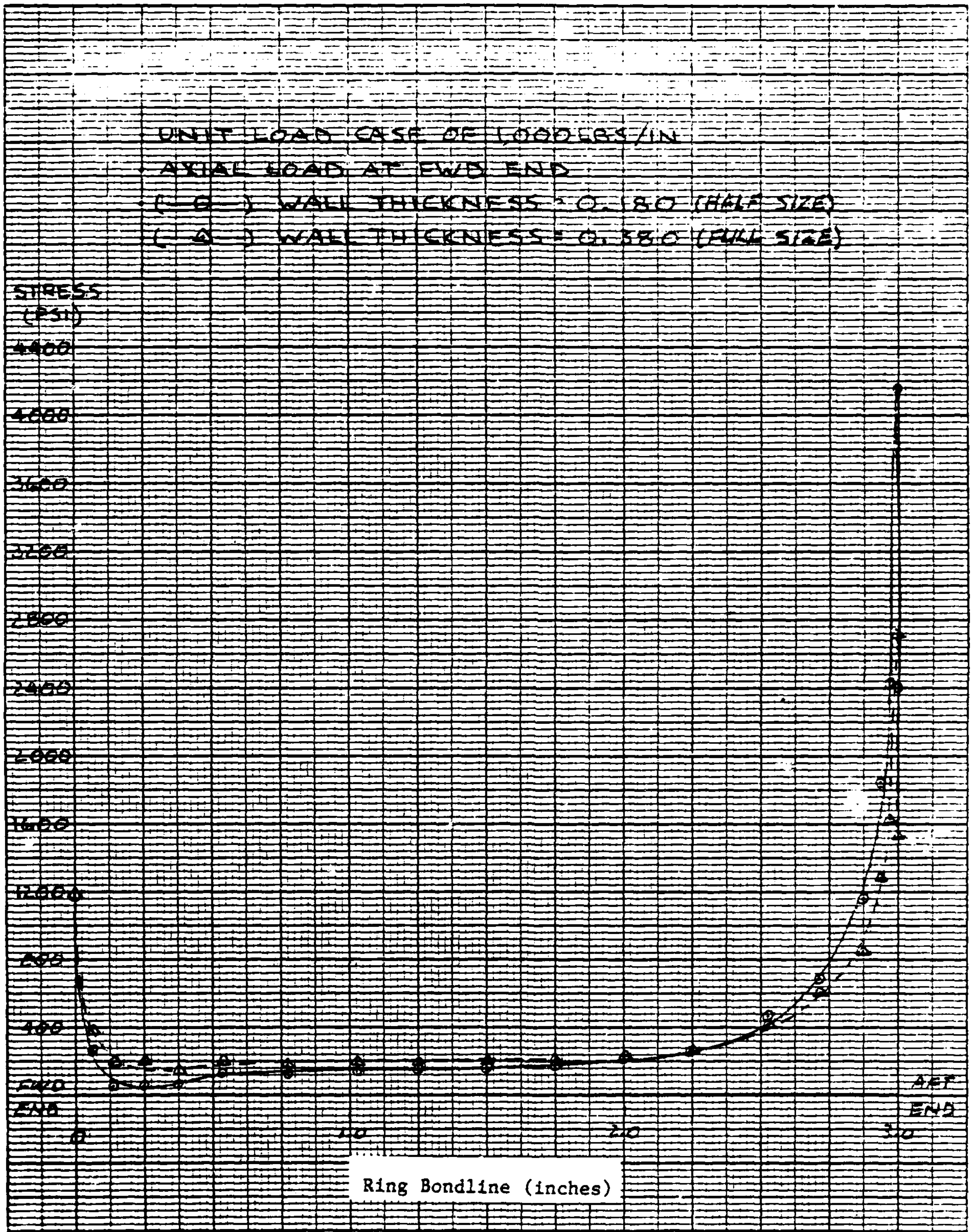

Figure 7-4. Shear Stress Distribution in the Bond Joint Between an Equipment Ring and a Frustum.

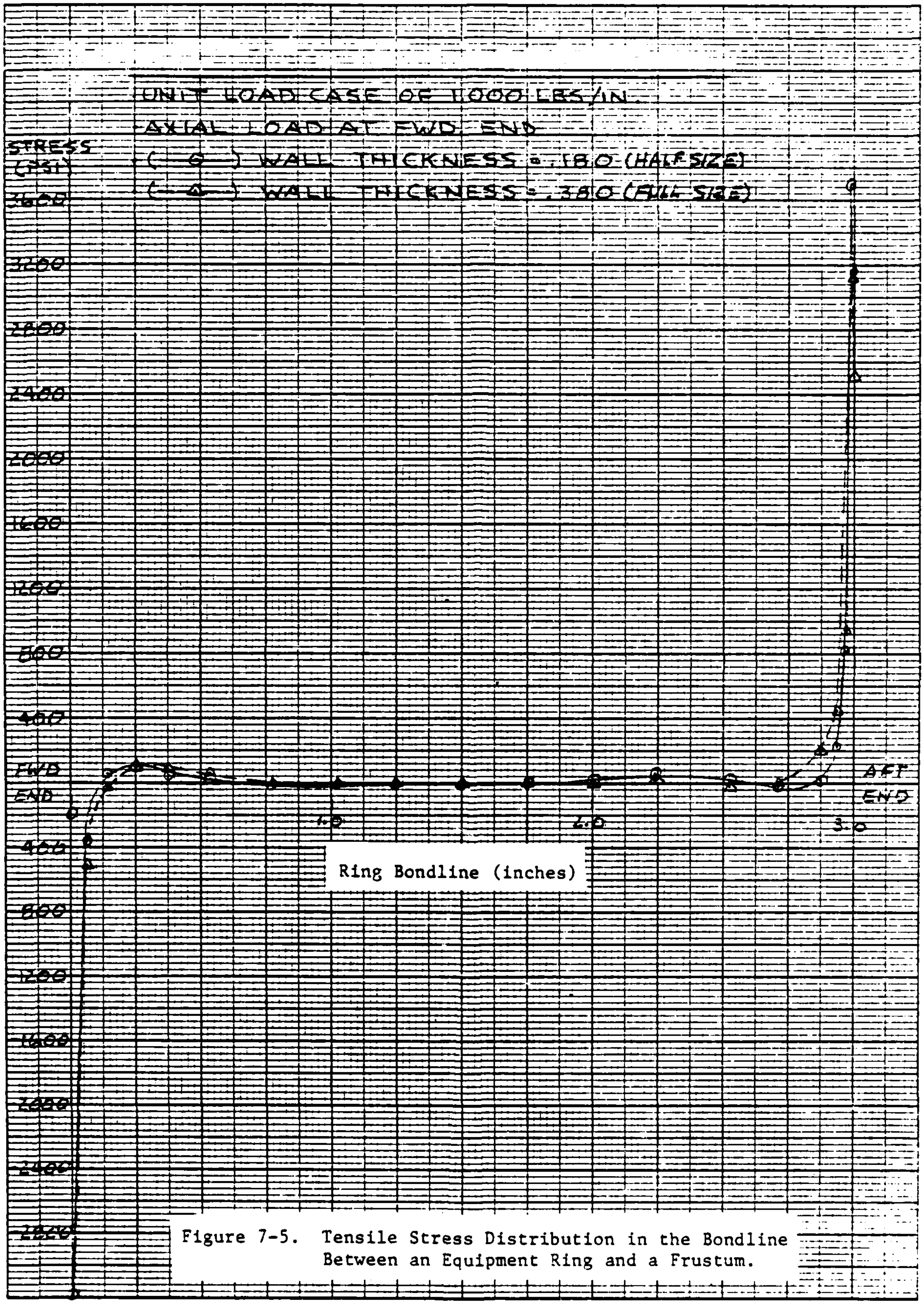

Figure 7-5. Tensile Stress Distribution in the Bondline Between an Equipment Ring and a Frustum.

a decrease from 3,710 psi to 3,117 psi for a 16% decrease in peak tensile stress with the thicker wall. There is also an increase in compressive stress at the forward end of the bondline. Compressive stress increases from 3,182 psi to 3,624 psi for an increase of 13.9%.

3. Effects of forward versus aft end loading: Changing the point of load application from the forward end to the aft end principally affects the tensile stress in the bondline. In the case of the thin wall frustum the peak shear stress decreased from 4,160 psi to 3,906 psi for a decrease of 6.1%. Peak tensile stress, however, went from 3,710 psi to 3,257 psi for a decrease of 12.2%. In the case of the thick wall frustum, the peak shear stress decreased from 4,160 psi to 3,906 psi for a decrease of 6.1%. Peak tensile stress, however, went from 3,710 psi to 3,257 psi for a decrease of 12.2%. In the case of the thick wall frustum, the peak shear stress decreased from 2,724 psi to 2,659 psi for a decrease of 2.4%. Peak tensile stress, however, went from 3,117 psi to 2,932 psi for a decrease of 5.9%. Figures 7-6 and 7-7 are plots of tensile stress distribution comparing forward end loading with helicoil (aft end) loading.

4. Stress at test load failure: As discussed previously in section 6.3.1, the test structure failed in the bondline at an axial loading of 73,800 lb. Load case 1 represented this condition and indicated a peak shear stress of 10,513 psi occurred just forward of the aft end of the ring. Figure 7-8 shows the shear and tensile stress distribution for this load condition. It should be noted that the typical tensile shear strength of the adhesive is 3,100 psi. It would appear that there is an additional mechanism which permits further redistribution of the stress over and above that provided by the substitution of the plastic characteristics of the adhesive.

7.1.5 ANALYSIS OF FULL-SCALE STRUCTURE

The "large size" test frustum simulated a near full-scale structure (see Table 2-1 and 7-3) by having a maximum ring diameter of 9.75 inches and a cone half angle of 4.67°. This compares to full-scale structure which would have a maximum ring diameter of 11.0 inches and a cone half angle of 6.27°.

Table 7-3. Summary of Frusta Sizes

Dimension	"Large Size"	Full-Scale
Length (in.)	13.4	33.7
O.D. forward (in.)	8.54	8.01
O.D. aft (in.)	10.73	15.41
Thickness (in.)	0.18	0.38
Cone angle (deg.)	4.67	6.27

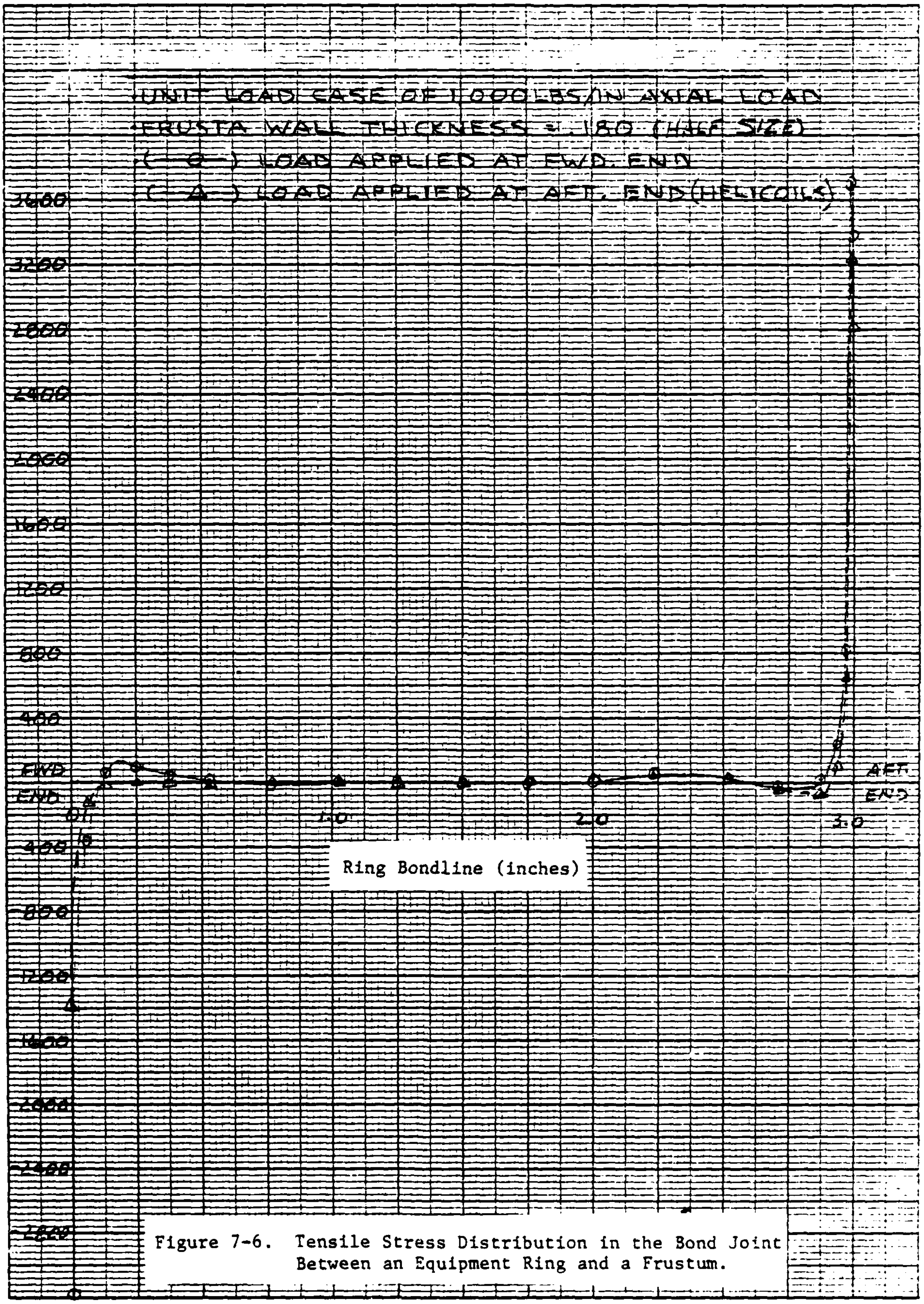

Figure 7-6. Tensile Stress Distribution in the Bond Joint Between an Equipment Ring and a Frustum.

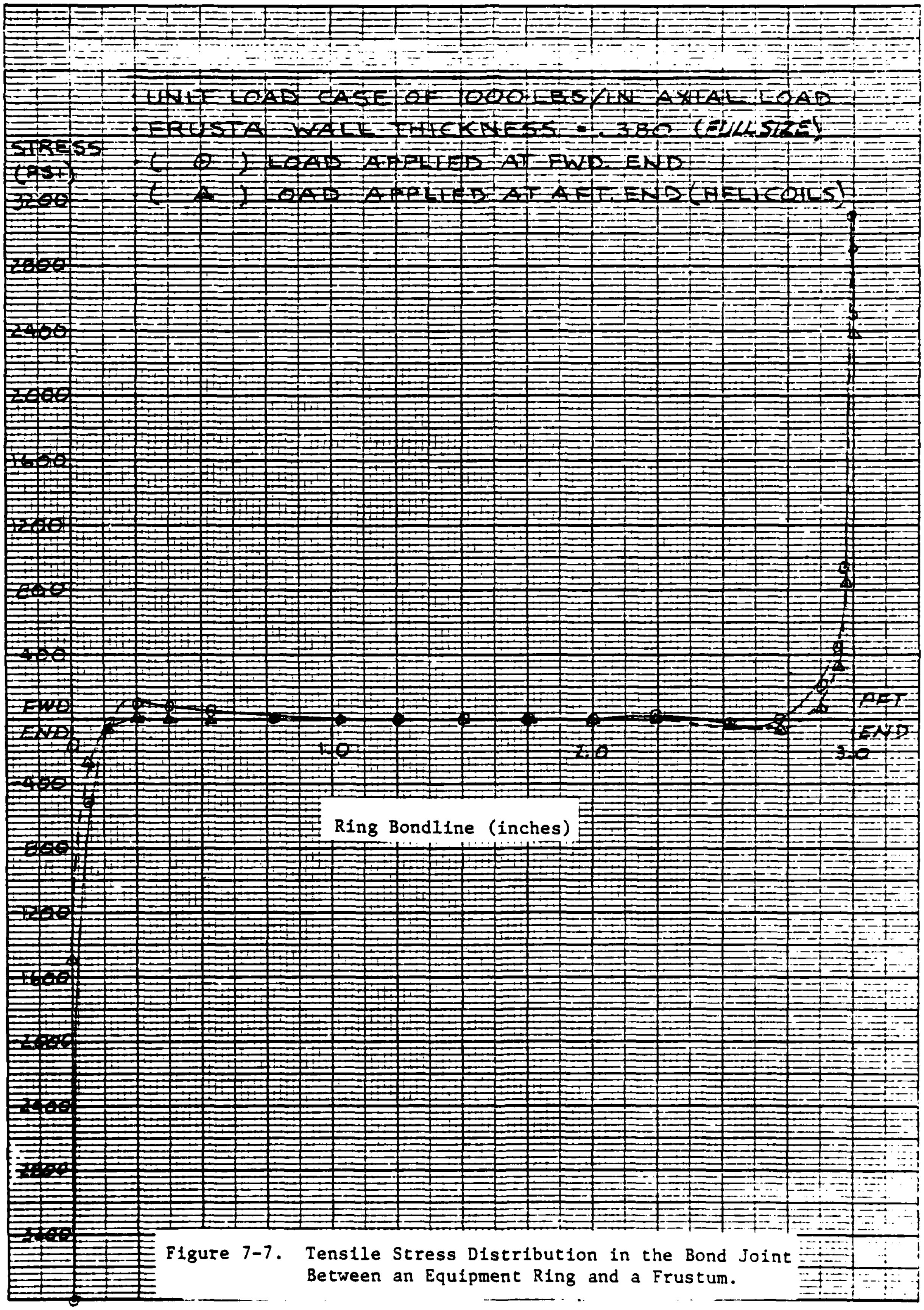

Figure 7-7. Tensile Stress Distribution in the Bond Joint Between an Equipment Ring and a Frustum.

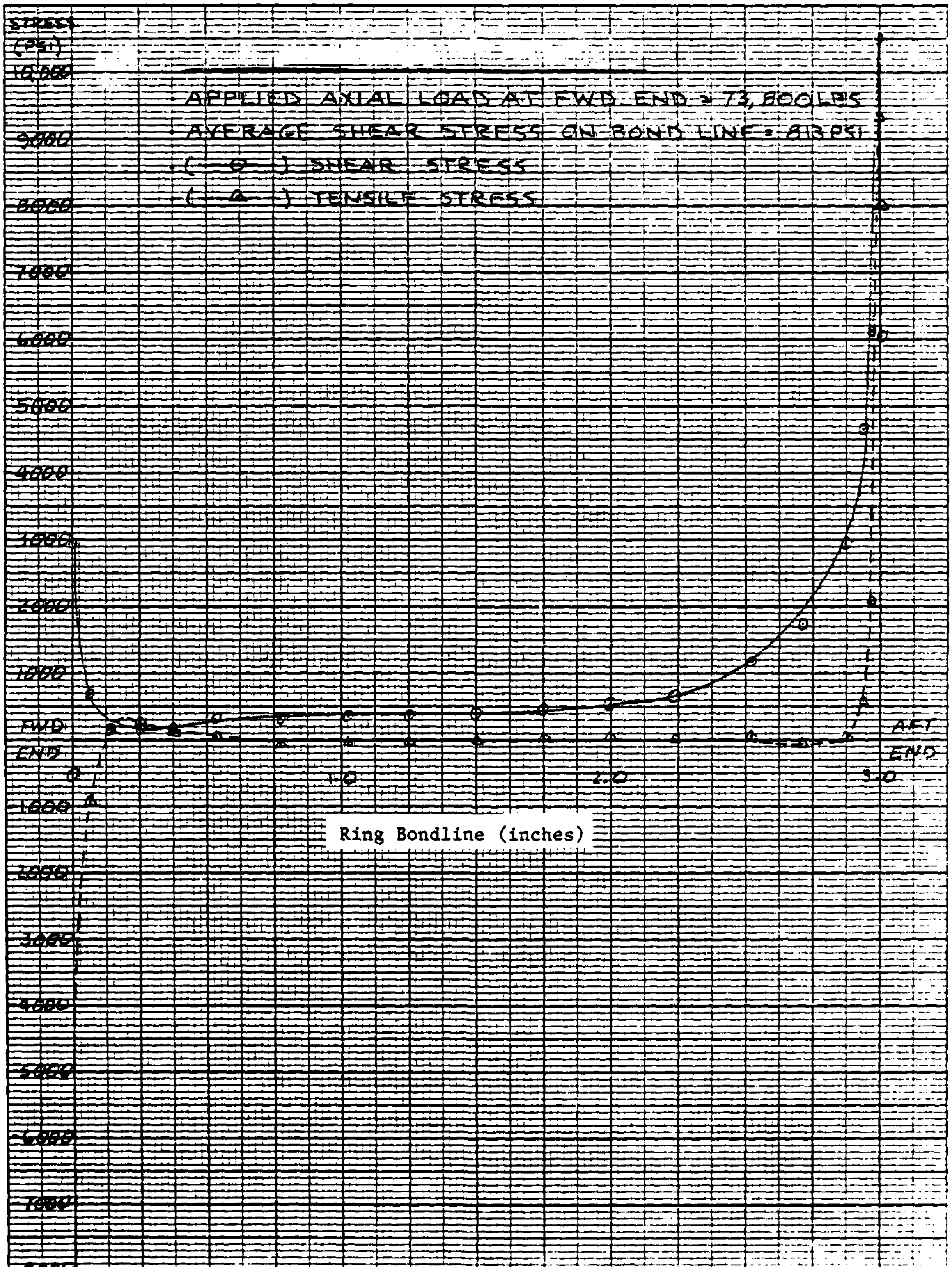

Figure 7-8. Test Load Stress Distribution in a Bond Joint Between an Equipment Ring and a Frustum.

Because the diameters at the equipment ring locations are nearly equal, it was determined that the finite element model analysis of the test frustum failure could be used for the full-scale structure. This analysis has a built in conservative basis because the full-size ring is slightly larger.

The finite element model indicated the test unit failed when the peak stresses reached 9,374 psi tensile stress in the radial direction and 10,513 psi shear stress in the axial direction. This represents a combined stress failure and so, to find the maximum tensile and shear stresses, it is necessary to use Mohr's circle. Figure 7-9 shows the Mohr's circle developed from the results of the finite element analysis.

The maximum loads applied to a full sized equipment ring (Reference 4) are:

		Limit Load	Ultimate Load
P =	Axial Load (axis 1 in Figure 7-1)	= 36,000 lb	54,000 lb
V =	In-Plane Load (axis 2 in Figure 7-2)	= 12,700 lb	19,050 lb

Maximum ultimate shear flow (q^V) due to the In-Plane load:

$$q^V = \frac{V}{\pi D/2}$$ where D = 10.250 (Helicoil Bolt Circle for full scale unit - Figure 2-1)

$$q^V = \frac{19,050(2)}{\pi(10.250)} = 1183 \quad \text{lb/in}$$

Shear Stress due to In-Plane Load (T^V):

$$T^V_{MAX} = \frac{q^V}{L}$$ where L is the length of the ring

$$= \frac{1183}{3.00} = 394 \quad \text{psi}$$

Maximum Interlaminar Shear T^A:

$$T^A = \frac{P}{\pi D} \times \frac{\text{(Shear Stress at Unit Load)}}{\text{(Unit Load)}}$$ where the stress at unit load is derived from the finite element model L.C.3

$$= \frac{54,000}{\pi(10.250)} \left[\frac{2,883}{1,000}\right]$$

$$T^A = 4,835 \text{ PSI}$$

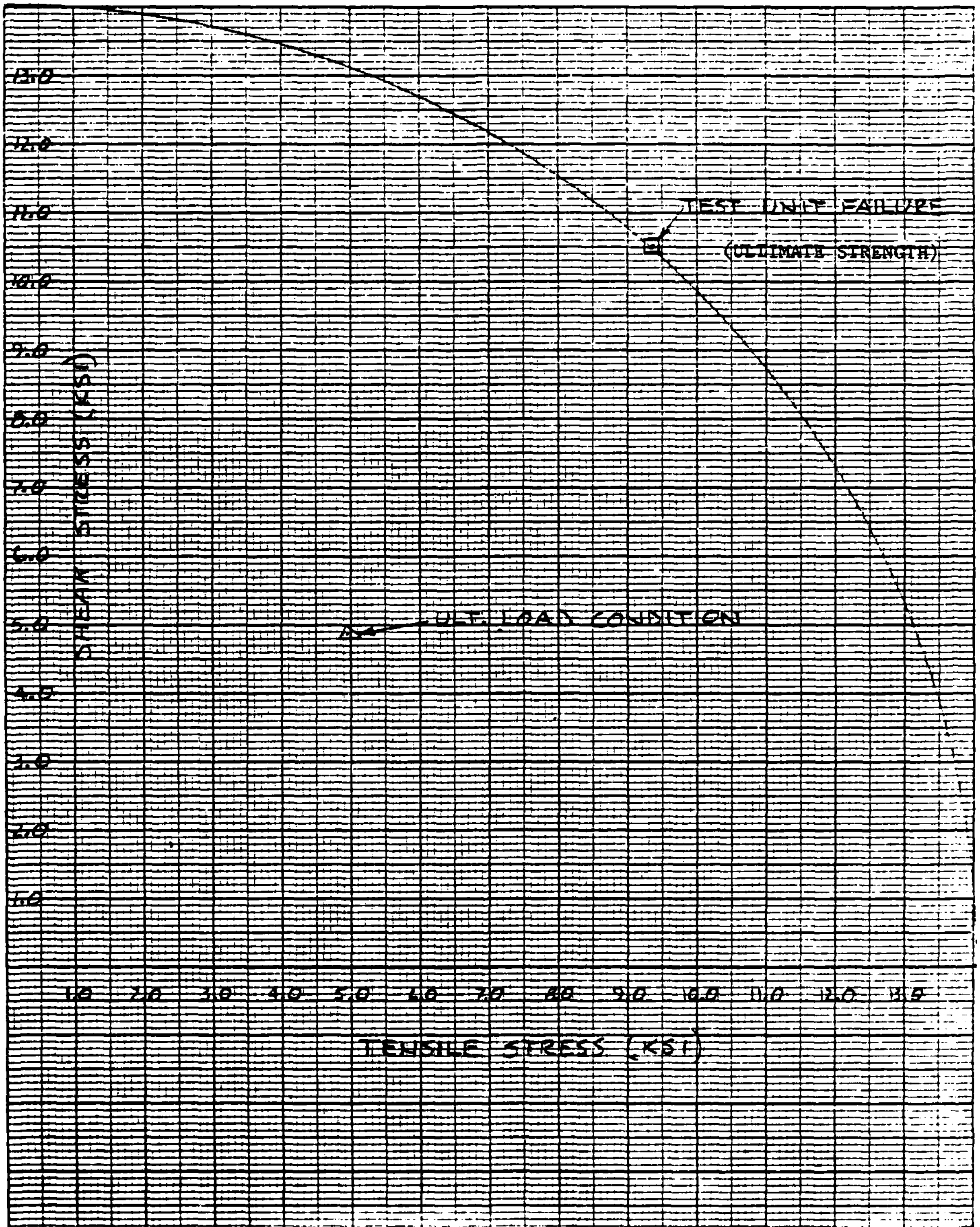

Figure 7-9. Mohr's Circle Combined Stress Analysis

Resultant Maximum Shear (T^R):

$$T^R_{MAX} = [(394)^2 + (4,835)^2]^{1/2}$$

$$= 4,851 \text{ PSI}$$

Maximum Interlaminar Tension (σ^{it}):

$$\sigma^{it} = \frac{P}{\pi D}\left[\frac{\text{Tensile Stress at Unit Load}}{\text{Unit Load}}\right]$$ where the tensile stress at unit load is derived from the finite element model L.C.3

$$\sigma^{it} = \frac{54,000}{\pi(10.250)} \left[\frac{2,932}{1,000}\right]$$

$$= 4,917 \text{ PSI}$$

MARGIN OF SAFETY

$$\text{M.S.} = \frac{\text{Ult. Strength}}{\text{Ult. Load}} -1$$ (see Figure 7-9)

The ult. strength obtained from the finite element model and shown in Figure 9 is:

$$\text{Ult. Strength} = [(9,374)^2 + (10,513)^2]^{1/2}$$

The ult. load is:

$$\text{Ult. Load} = [(4,917)^2 + (4,851)^2]^{1/2}$$

$$\therefore \quad \text{M.S.} = \frac{[(9,374)^2 + (10,513)^2]^{1/2}}{[(4,917)^2 + (4,851)^2]^{1/2}} -1 = +1.0$$

A margin of safety of +1.0 means the design will carry twice the design ultimate load.

7.1.6 Finite Element Study Conclusions

The bonded ring has been analyzed and results obtained from structure testing and finite element analysis have been compared. This analysis indicates a margin of safety of over 1. Therefore, it can safely be assumed that the proposed ring design will carry twice the design ultimate loads.

7.2 STABILITY ANALYSIS

The stability of the graphite/epoxy frustum was verified by the use of BOSOR4. BOSOR4 is a comprehensive computer program for the stress, stability, and vibration analyses of segmented, ring-stiffened, branched shells of revolution. The program includes nonlinear prestress effects and is very general with respect to geometry of meridian, shell wall design, edge conditions, and loading. The computer program has been verified by comparisons with other known solutions and test results. The stability option results in a linear bifurcation analysis, where the critical nonlinear prestress is assumed to be distributed axisymmetrically.

7.2.1 Mathematical Model

The mathematical model is formulated from the geometry of the structure and the mechanical properties of the shell wall and the intermediate ring. The end rings are not included because no data is available. Also, the antenna cutouts are excluded because asymmetric structure cannot be accommodated by BOSOR4, and this region is only critical for high stress, not buckling. Accordingly, for the stability analysis the thicker walls at both ends were neglected. The geometry of the frustum is shown in Figure 7-10, and the dimensions of the intermediate ring are shown in Figure 7-11. The properties of the ring were obtained by use of a Hewlett-Packard 67/97 calculator, and the results were

$$A = 1.520 \text{ in}^2 \qquad I_x = 0.053 \text{ in}^4$$

$$sc = 1.242 \text{ in} \qquad I_y = 0.984 \text{ in}^4$$

$$zc = 0.282 \text{ in} \qquad I_{xy} = -0.092 \text{ in}^4$$

When A is the area and I is the section modulus about the various axis.

7.2.2 Material Properties

For the mechanical properties of the frustum shell wall (GY-70/934) and the intermediate ring (T-300/934) refer to Table 7-1. As noted earlier, the basic shell wall is assumed constant for the full length of the model.

7.2.3 Design Limit Loads

The critical design loads are for first stage burnout (Reference 4), which are shown on the structure in Figure 7-12. In this case the loads are those for condition 4A rather than a combination of 4A and 4C loadings. The pressure loads acting to the right represent the combination of inertia and air pressure (on opposite side) loads. This was simplified to two uniformly distributed loads to facilitate the computer coding.

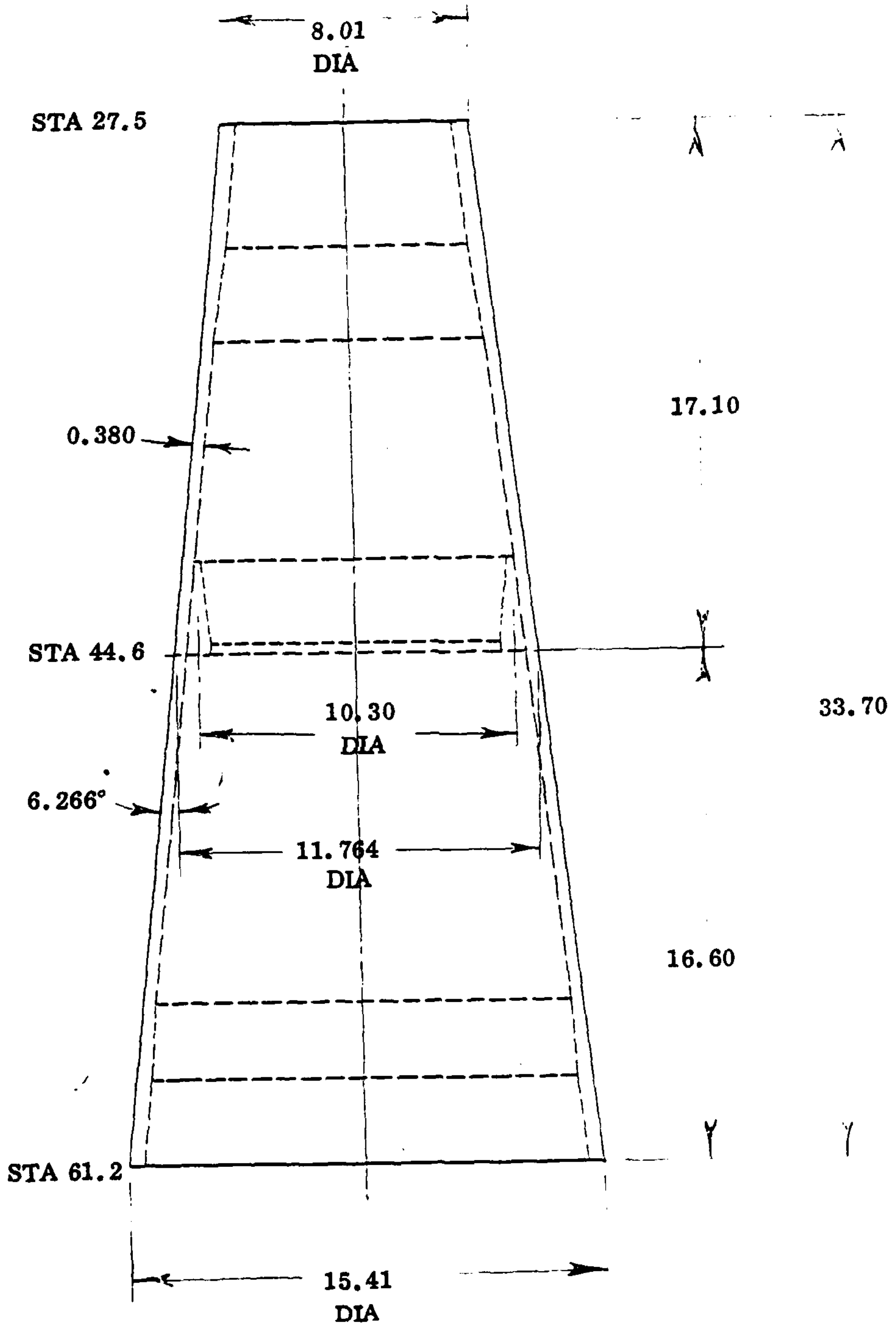

Figure 7-10. Full Sized Frustum Geometry

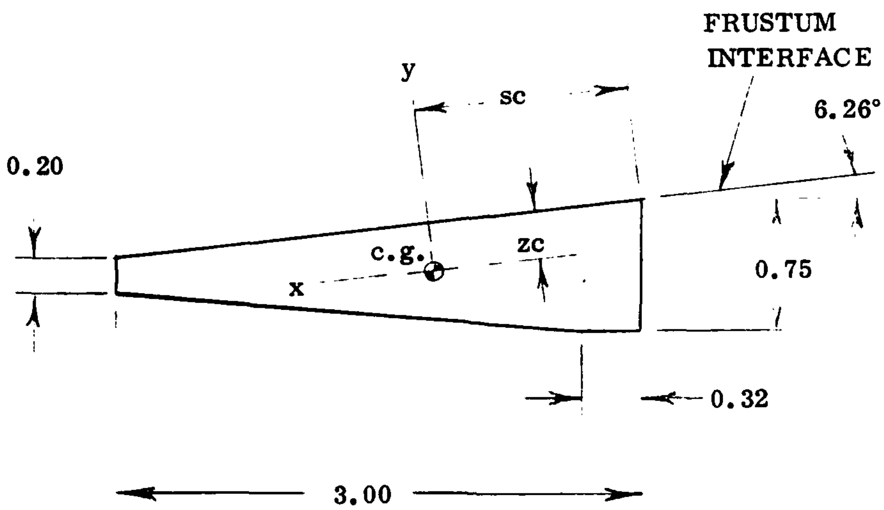

Figure 7-11. Intermediate Ring Cross-Section

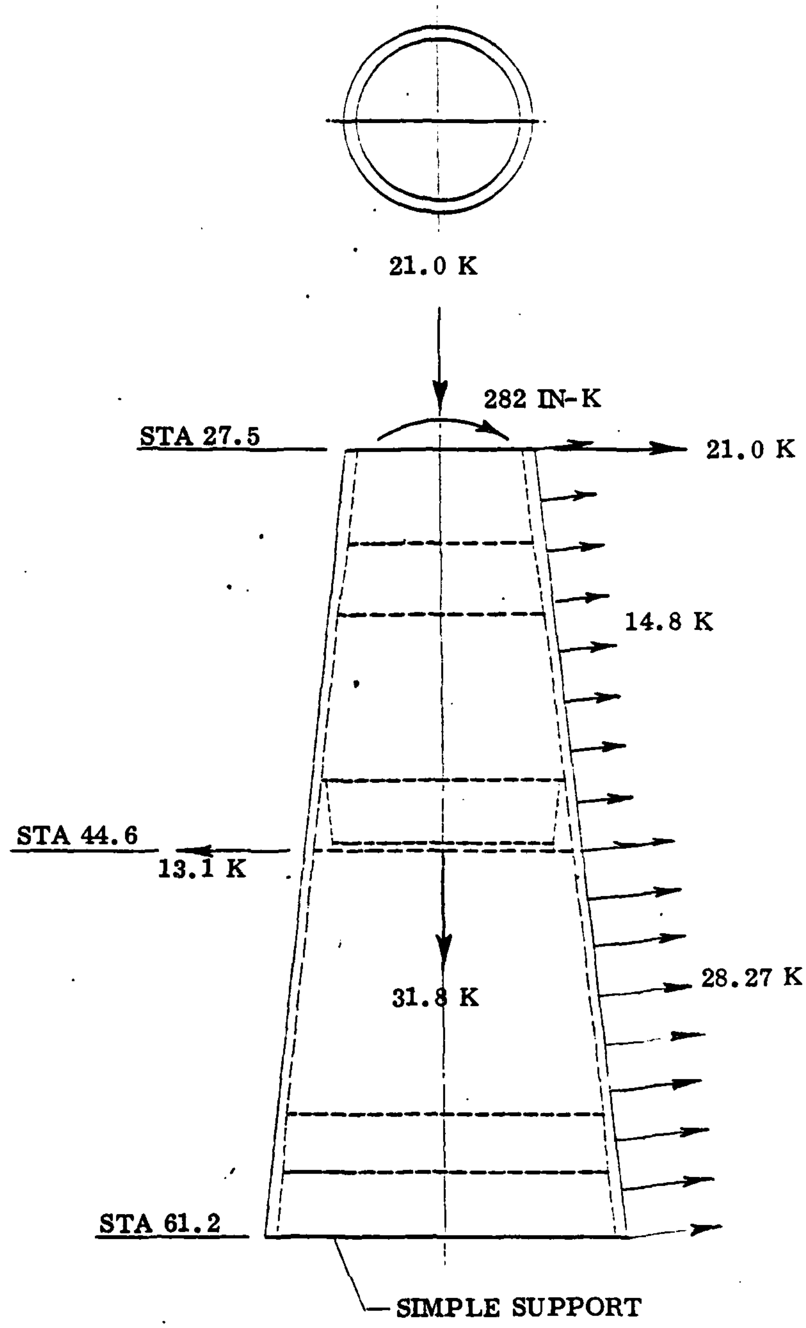

Figure 7-12. First Stage Burnout Design Limit Loads for Configuration 4A on Frustum.

7.2.4 BOSOR4 Loads

The loads shown in Figure 7-12 must be converted to appropriate loads to accommodate the loads routines of the BOSOR4 code. Accordingly, the loads for the BOSOR4 stability analysis are shown in Figure 7-13.

The transverse shear loads at stations 27.5 and 44.6 are replaced by shear tractions 1752 sin θ and -810 sin θ, respectively. The transverse shell loads are approximately simulated by pressure loads as shown in Figure 7-13. The loads shown result in somewhat conservative loads at the supported end.

7.2.5 Bifurcation Buckling

The BOSOR4 model was formulated into two segments with 50 mesh points along the length. Segment 1 is located from Sta. 61.2 (mesh point 1) to Sta. 44.6 (mesh point 25); segment 2 is located from Sta. 44.6 (mesh point 26) to Sta. 27.5 (mesh point 50). The edge of segment 1 at mesh point 1 is simply-supported, which provides reactions to the loads shown in Figure 7-13. The intermediate ring was located at mesh point 25 of segment 1. Compatibility was maintained at the juncture of the two segments.

The results of the stability analysis are presented as follows:

Minimum Eigenvalue:

λ = 13.3 (critical near Sta. 61.2)

3. circumferential full waves

2.5 longitudinal half-waves

Thus, the classical bifurcation buckling loads are 13.3 times the limit loads shown in Figure 7-13, and the knock-down factor for the frustum is negligible. The case considered here was for configuration 4A. Since configuration 4C is only slightly different the conclusions for it would be the same. The margin of safety for buckling is high, and need not be considered further.

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DEVELOPMENT OF ADVANCED INTERCEPTOR SUBSTRUCTURAL MATERIAL.(U)
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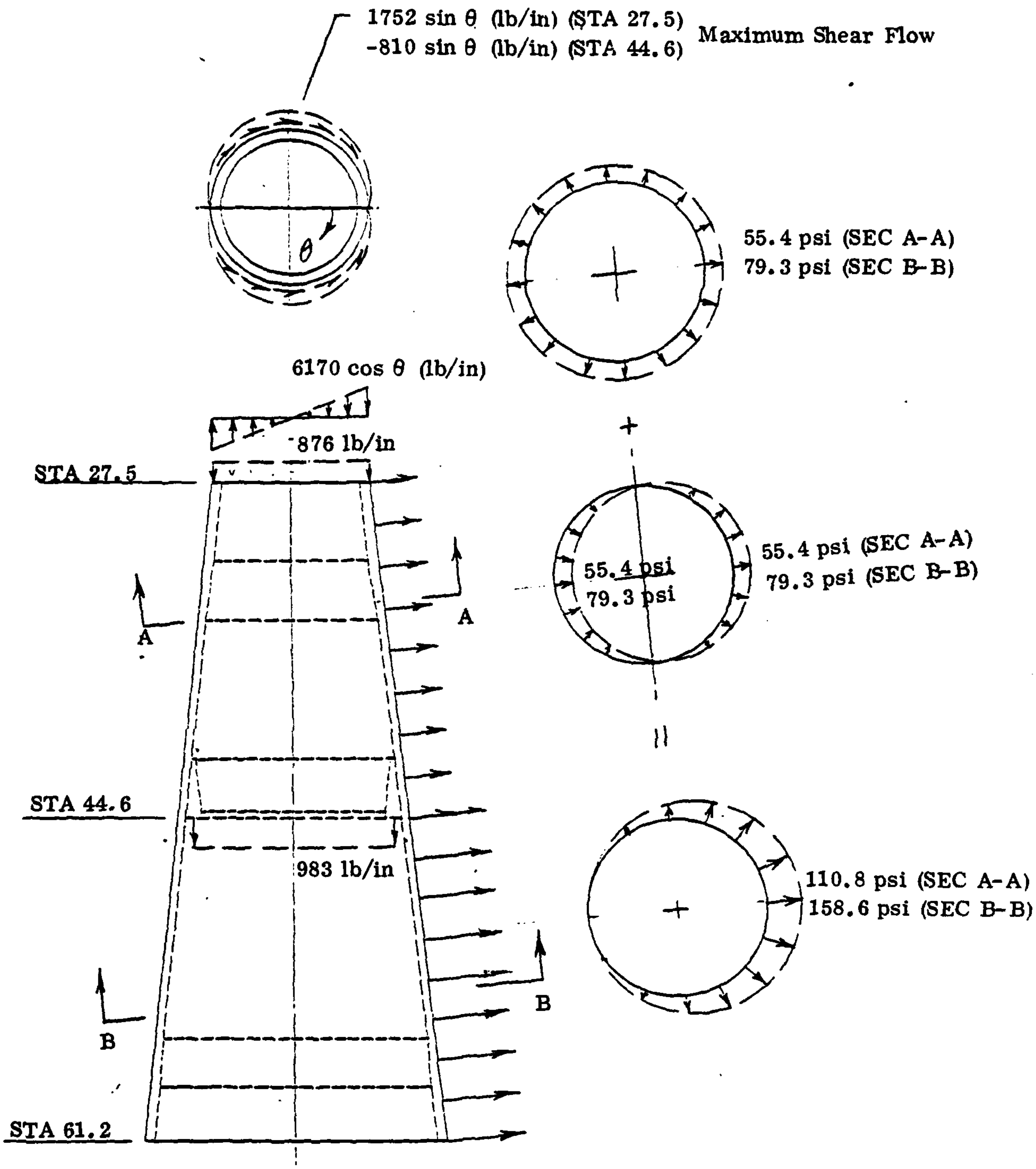

Figure 7-13. BOSOR4 Model Loads

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SECTION 8

FULL SIZED FRUSTUM DESIGN

8.1 Preliminary Design

A preliminary design of the full sized guidance and control section of an advanced terminal interceptor was given in Reference 4. This design is reproduced in Figure 2-1. The aim of this program was to finalize the design so that a prototype frustum could be manufactured.

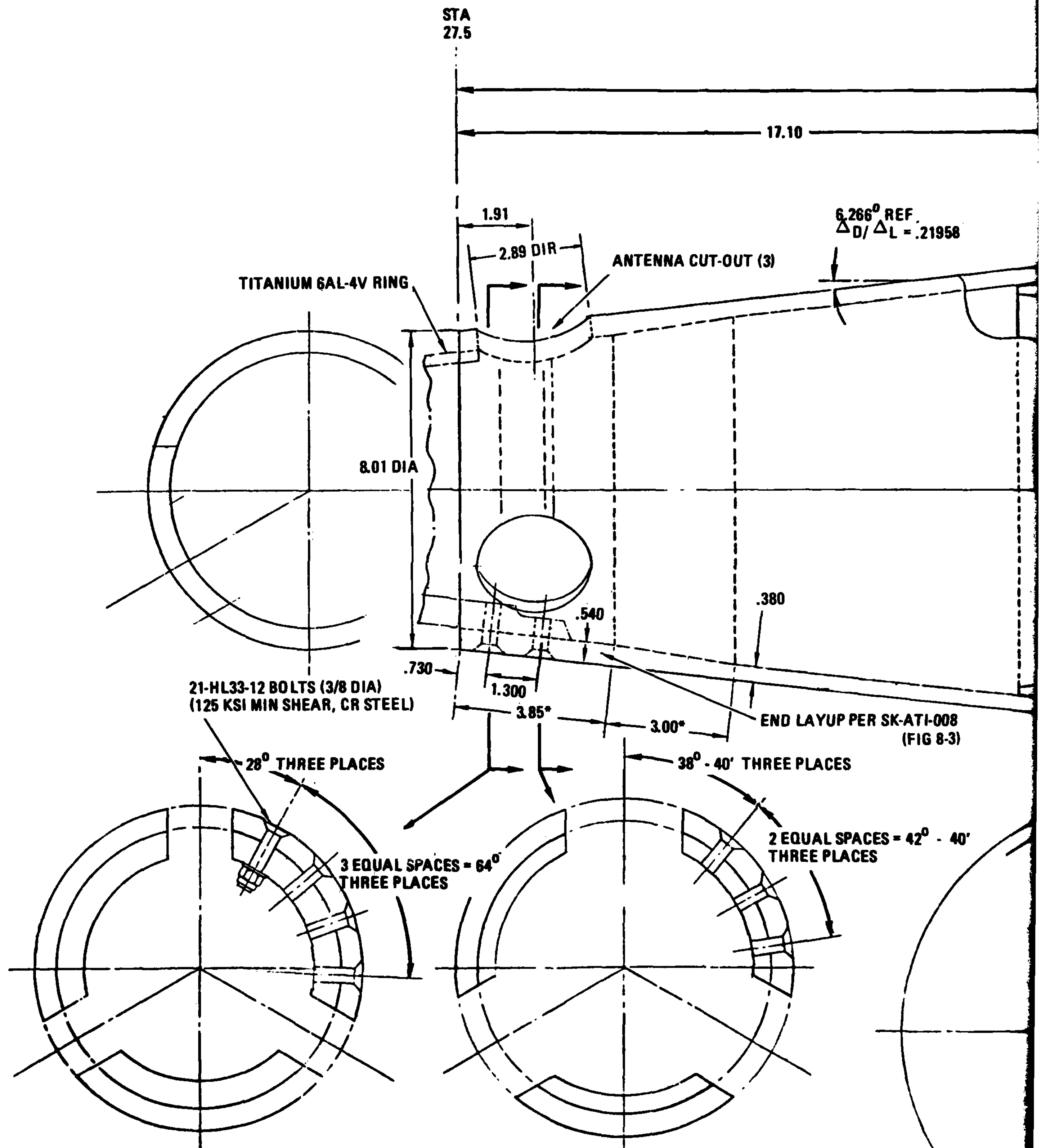
8.2 Design Modification

The objective of this task was to take the preliminary design and modify it as necessary based upon the findings of this contract. The discussions in sections 6 and 7 show that the preliminary design is adequate. The splices caused by fabricating a frustum from gore sections do not affect the strength or modulus of the frustum. The end joints are adequate to take the required loads as proven by coupon tests. The forward end of the full-sized frustum is capable of withstanding the required loads in spite of rather large cut-outs.

Based upon these findings and the previous finding the design is ready for use in fabricating a full-sized prototype. That design is shown in Figure 8-1.

8.3 Tool Design

The tool necessary to fabricate a prototype full-scale frustum is shown in Figure 8-2. The tool inside contour is controlled by the required external size of the frustum which is controlled by the design of the total vehicle. This was defined in Reference 1. The tool was made of both graphite because the tools for fabricating the subscale frusta were graphite which has proven highly reliable.



STA
27.5
17.10
1.91
2.89 DIR
ANTENNA CUT-OUT (3)
6.266° REF
ΔD/ΔL = .21958
TITANIUM 6AL-4V RING
8.01 DIA
.540
.380
.730
1.300
21-HL33-12 BOLTS (3/8 DIA)
(125 KSI MIN SHEAR, CR STEEL)
3.85*
3.00*
END LAYUP PER SK-ATI-008
(FIG 8-3)
28° THREE PLACES
38° - 40' THREE PLACES
3 EQUAL SPACES = 64°
THREE PLACES
2 EQUAL SPACES = 42° - 40'
THREE PLACES

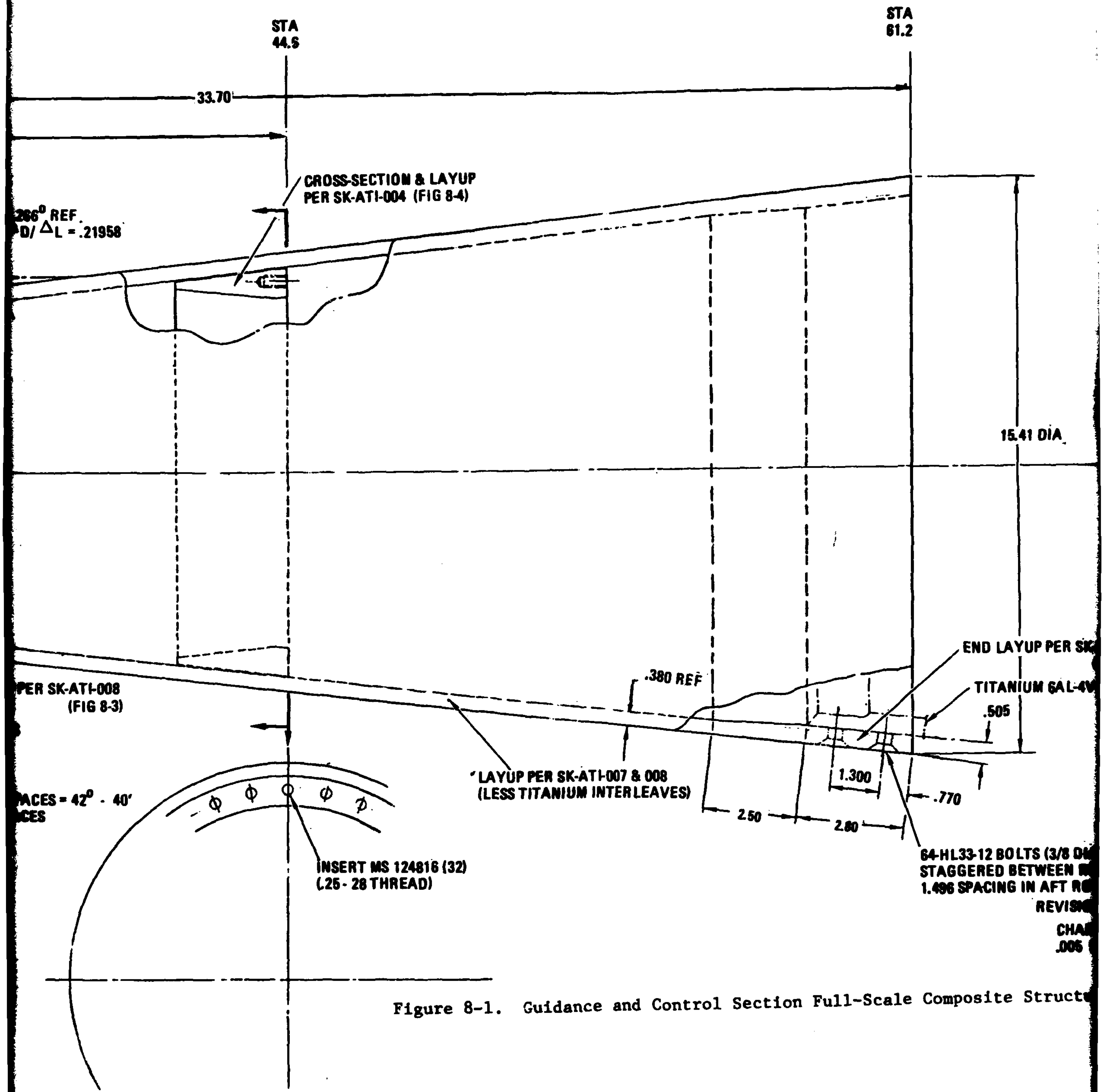


Figure 8-1. Guidance and Control Section Full-Scale Composite Struct

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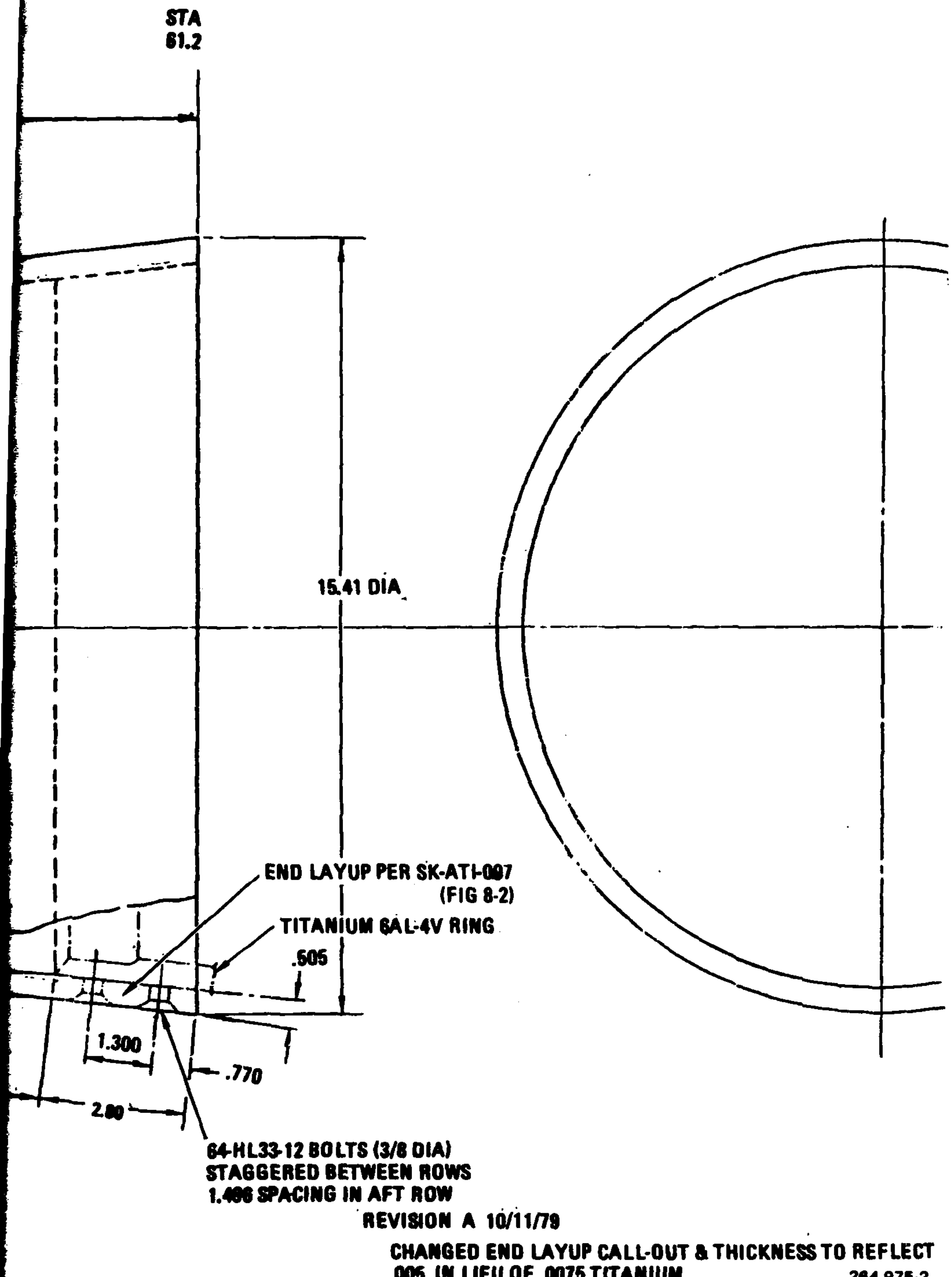
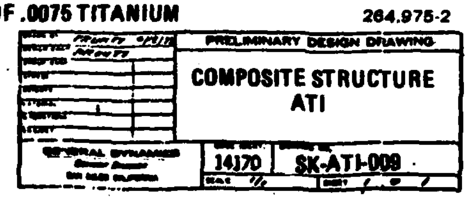
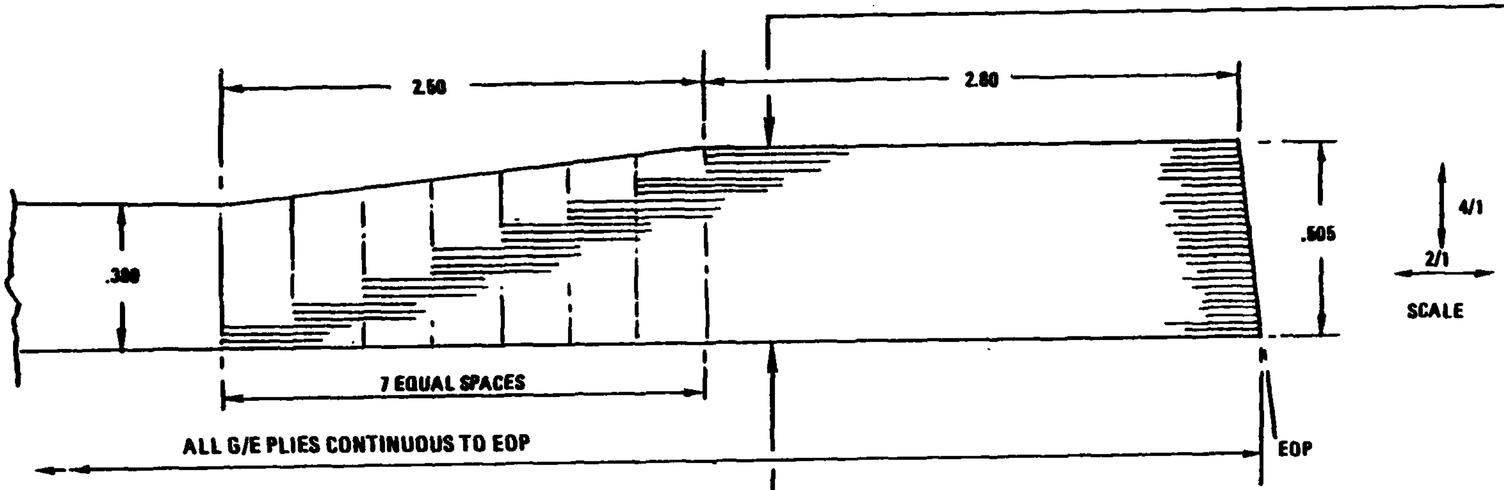




ion Full-Scale Composite Structure

, 3

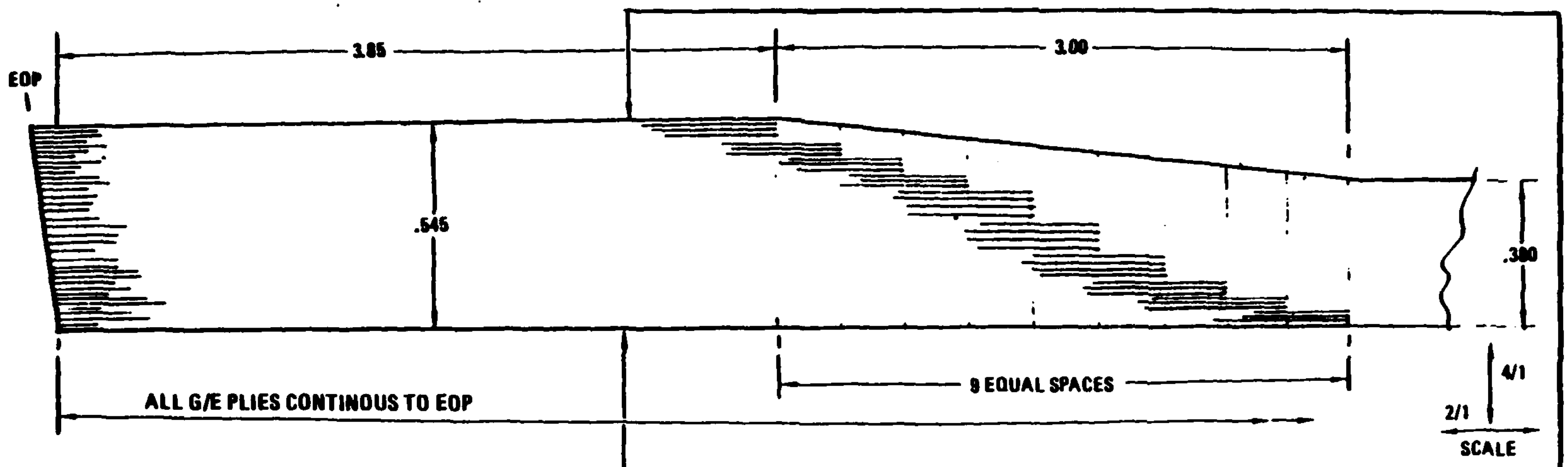


MATERIALS:
PLIES # 1 - 76 G/E GY70/934
TA1 - TA25, .005 TITANIUM 6 AL-4V ANNEALED

SEQUENCE	PLY NO	ORIENTATION
A	1	0
	2	0
	3	45
	TA1	TI
	4	90
	5	135
	TA2	TI
	6	90
	7	45
	8	0
	TA3	TI
	9	0
	10	0
	11	135
	TA4	TI
	12	0
	13	0
	14	0
	TA5	TI
	15	45
	16	0
	17	0
	TA6	TI
	18	135
	19	0
	20	0
	TA7	TI
	21	135
	22	0
	23	0
	TA8	TI
	24	45
	25	0
	26	0
	TA9	TI
	27	0
	28	135
	29	0
	TA10	TI
	30	0
	31	0
	32	45
	TA11	TI
	33	90
	34	135
	35	90
	TA12	TI
	36	45
	37	0
	38	0
B	TA13	TI
C	39 ↔ 76	REPEAT "A" IN REVERSE DESIGNATE TI TA14 - TA25

264.975-3

Figure 8-2. Aft End Splice Lamination



MATERIALS:
PLIES # 1 - 76 G/E, GY70/934
TF1 - TF33 -.005 TITANIUM, 6AL-4V ANNEALED

SEQUENCE	PLY NO	ORIENTATION
C	76 – 39	REPEAT "A" IN REVERSE
B	TF17	TI
A	38	0
	37	0
	36	45
	TF16	TI
	35	90
	34	135
	33	90
	TF15	TI
	32	45
	31	0
	30	0
	TF14	TI
	29	0
	28	135
	TF13	TI
	27	0
	26	0
	TF12	TI
	25	0
	24	45
	TF11	TI
	23	0
	22	0
	TF10	TI
	21	135
	20	0
	TF9	TI
	19	0
	18	135
	TF8	TI
	17	0
	16	0
	TF7	TI
	15	45
	14	0
	TF6	TI
	13	0
	12	0
	TF5	TI
	11	135
	10	0
	TF4	TI
	9	0
	8	0
	TF3	TI
	7	45
	6	90
	TF2	TI
	5	135
	4	90
	TF1	TI
	3	45
	2	0
	1	0

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Figure 8-3 Forward End Splice Lamination

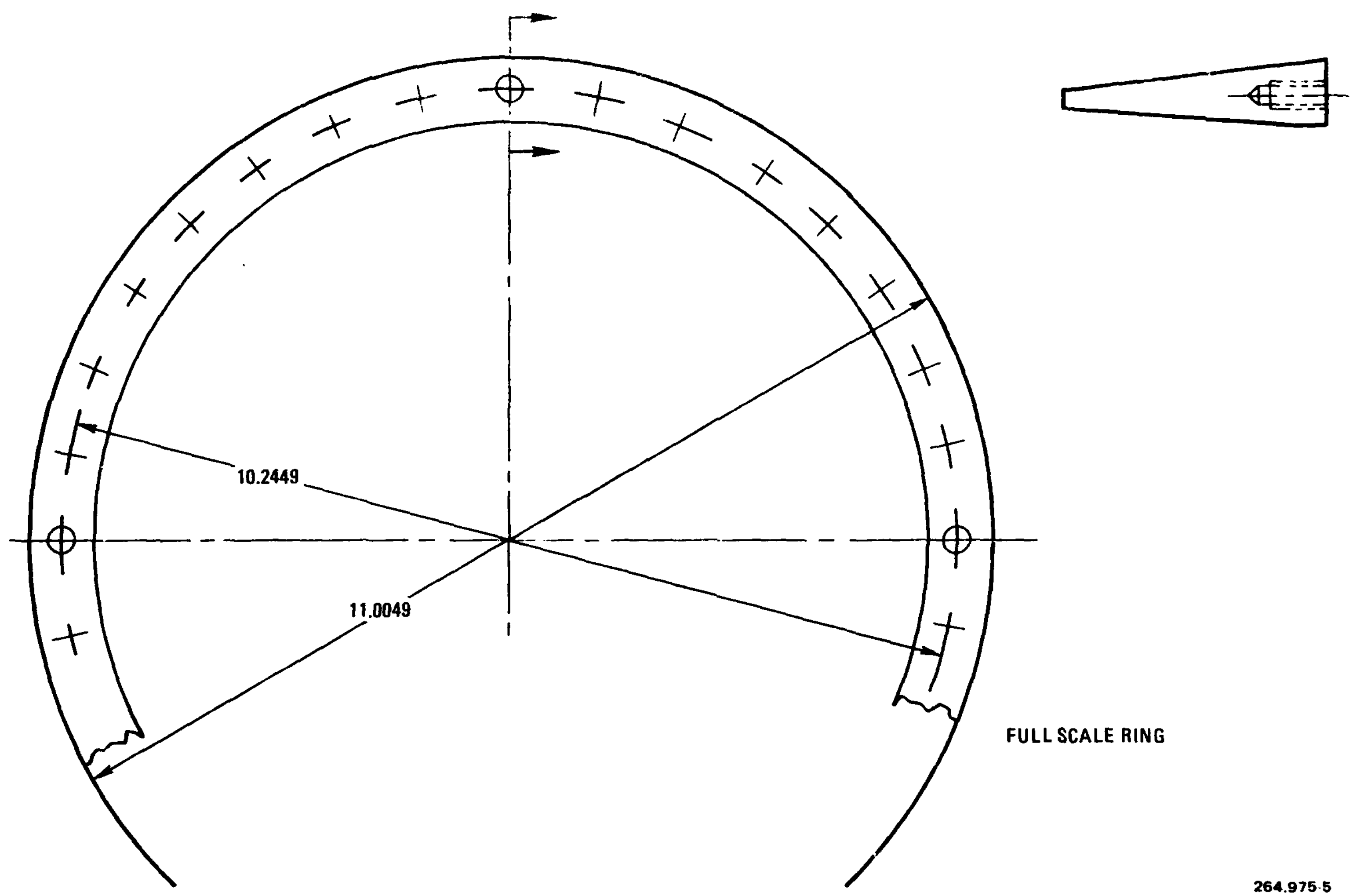


Figure 8-4. Equipment Ring Configuration for Composite Structures ATI.

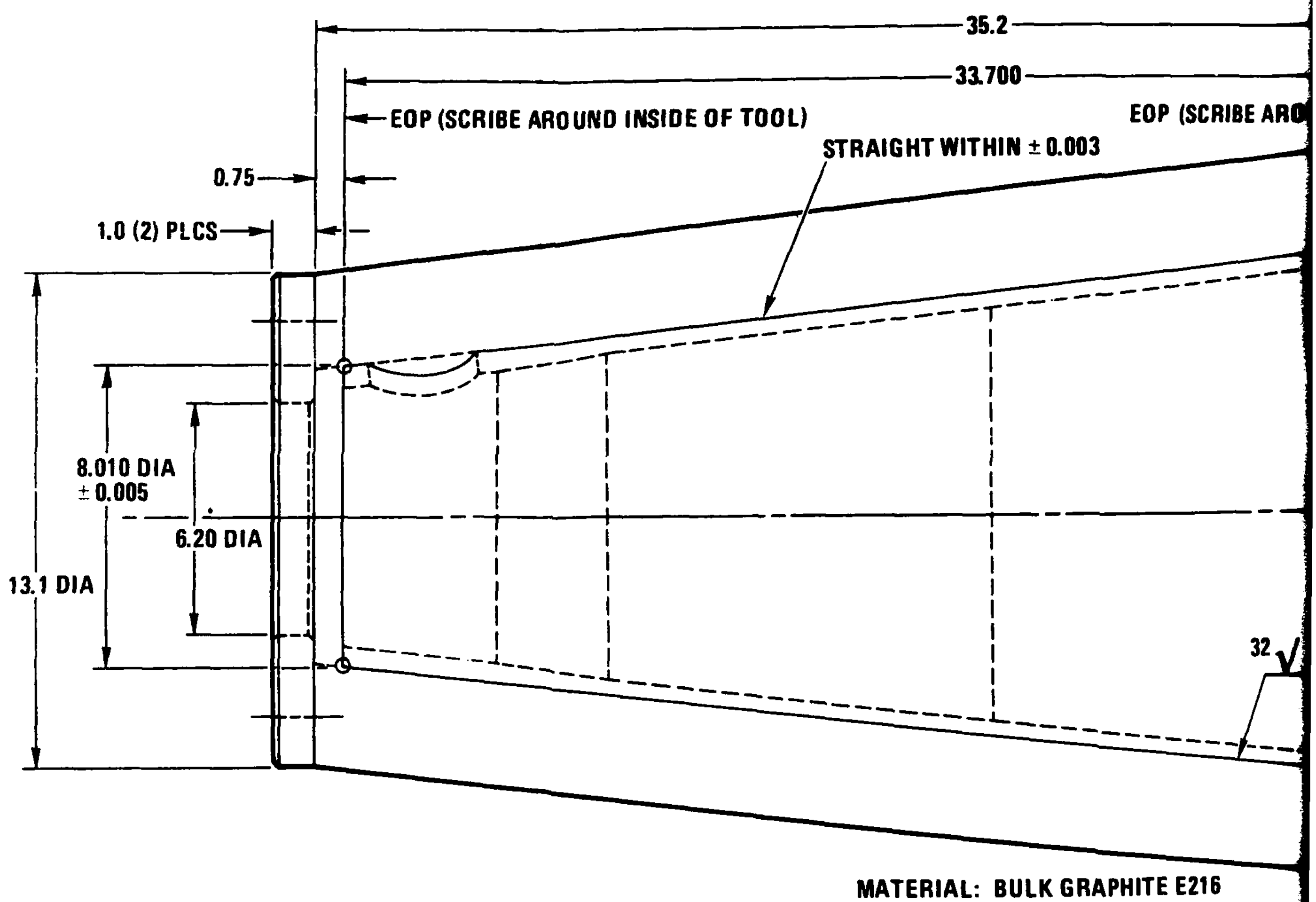
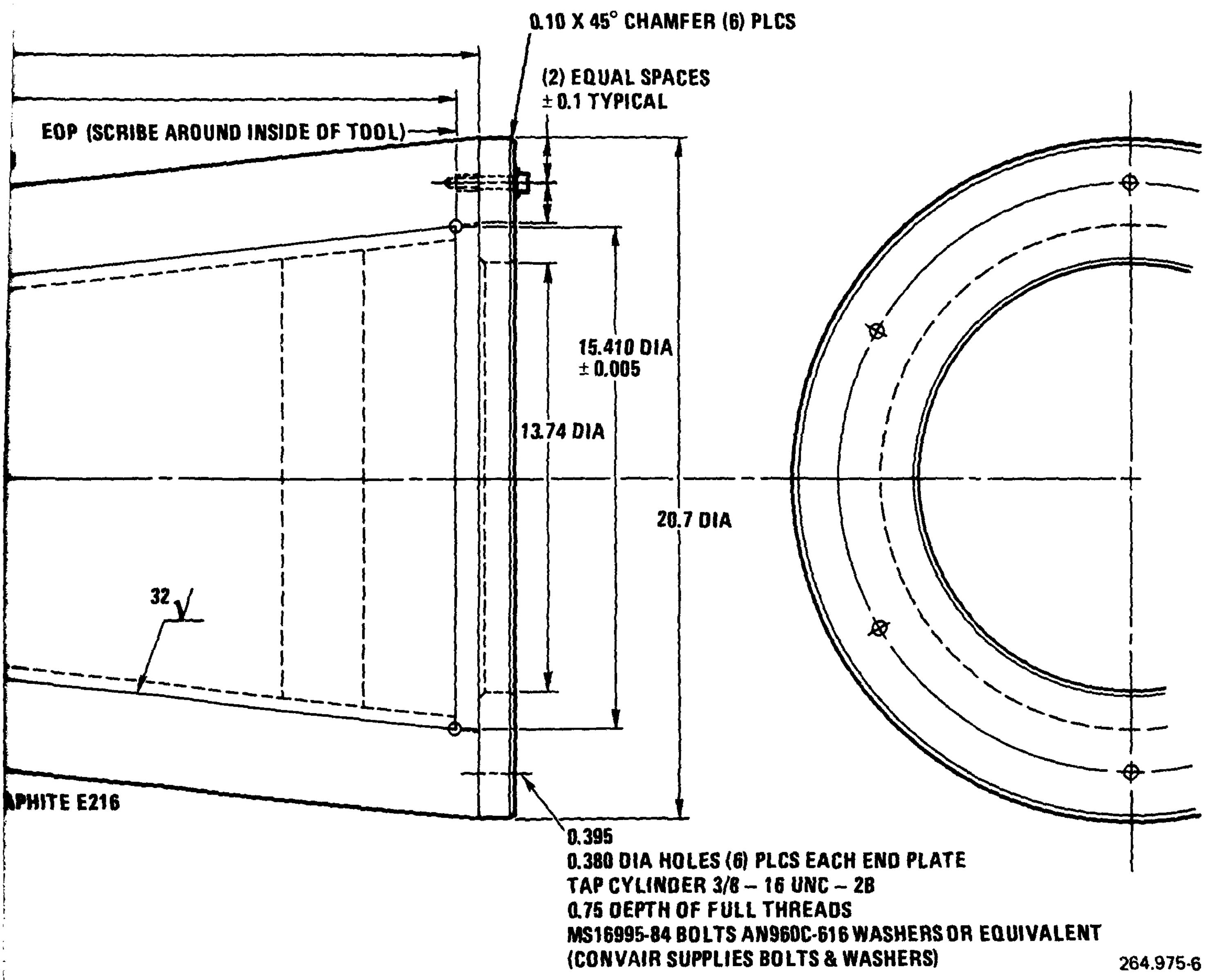


Figure 8-5. Mold Tool



5. Mold Tool for Full Sized Frustum

SECTION 9

MANUFACTURING PROCESS PLAN

A manufacturing process plan for the full-scale frustrum has been developed based on procedures previously proven under contracts DAAG46-78-C-0056 and DAAG46-76-C-0008. Figure 9-1 shows the sequence and flow which initiates with receiving inspection, is followed by fabrication of the frusta and equipment rings, and culminates with final assembly. The three major tasks, frusta fabrication, equipment ring fabrication and assembly are defined in detail in this section. Shown in Figures 9-2, 9-3 and 9-4 are block diagrams of each major task.

9.1 FRUSTUM FABRICATION PROCEDURE

1. Lay up 18 - 36" x 39" sheets of unidirectional GY-70/934 to prepare all gores needed for layup of plies 1-18. (The fibers are oriented in the 36" direction.) Record batch and roll numbers of all prepreg used in the layup.

2. Remove flanges from bulk graphite tool. Apply FreKote 33 to tool and bake for one hour at 300F, repeat three times. Reattach flanges and attach protractors to front and back ends of tool.

3. Cut titanium gores from 0.0050 inch thick 6A1-4V titanium foil sufficient for all plies needed per Table 9-1.

4. Prepare the titanium as follows:

   Cleaning: Immerse in solution of Oakite-HD126 (106 gm/2.5 gallons of water) at 140 to 180F for 5 to 15 minutes. Rinse with tap water at RT.

   Pickling: Immerse for two minutes maximum in solution of 2.0 to 3.0 fluid ounces/gallon HF and 40 to 50 fluid ounces/gallon HNO_3 at RT. Rinse titanium with tap water. Immerse for 1.5 to 2.5 minutes at RT in a solution of 6.5 to 7.0 ounces/gallon Na_3PO_4, 2.5 to 3.0 ounces/gallon of KF, and 2.2 to 2.5 fluid ounces/gallon of 70% HF. Rinse in tap water and follow with a 15 minute soak in deionized water at 145 to 155F.

   Storage: Place processed titanium between lint free cheese cloth and store at room temperature until ready for use. Note: All titanium to be handled with lint free white nylon gloves.

5. Lay up plies 1 to 3, plies TF-1*, TA-1*, plies 4, 5, plies TF-2, TA-2, plies 6, 7, ply TF-3, ply 8, ply TA-3 and ply 9 per Table 9-1. Preply after each ply of titanium (Ti) as a minimum.

6. Apply one ply of porous, Teflon coated glass cloth over the lay up, apply three plies of style 7581 glass fabric followed by 1/8-inch rubber overpress. Apply three plies of style 1534 glass fabric as vent. Place two thermocouples in the edge of the laminate and one on the tool. Bag for precompaction.

   *TF refers to titanium plies at forward end of frustum, and TA refers to titanium plies at aft end.

7. Precompact as follows: Apply a minimum of 24 inches of mercury, heat the part in an autoclave at 2-5F/minute to 160 ± 5F. Apply 50 psig autoclave pressure, hold 15 to 20 minutes and cool under vacuum and pressure to below 100F at a rate not to exceed 5F/minute.

8. Remove bag, vent, overpress, bleeder fabric, and Teflon-coated glass cloth.

9. Lay up ply TF-4, plies 10, 11, plies TF-5, TA-4, plies 12, 13 ply TF-6 ply 14, ply TA-5, ply 15, ply TF-7, plies 16, 17, plies TF-8, TA-6, ply 18 per Table 9-1. Preply after each ply of Ti as a minimum.

10. Repeat Step 6.

11. Repeat Step 7.

12. Repeat Step 8.

13. Lay up 18 sheets of unidirectional GY-70/934 to prepare all gores needed for plies 19 to 36. Record batch and roll numbers of all prepreg used in layup.

14. Lay up ply 19, ply TF-9, ply 20, ply TA-7, ply 21, ply TF-10, plies 22, 23, plies TF-11, TA-8, plies 24, 25, ply TF-12, ply 26, ply TA-9, and ply 27 per Table 9-1. Preply after each ply of Ti as a minumum.

15. Repeat Step 6

16. Repeat Step 7

17. Repeat Step 8

18. Lay up ply TF-13, plies 28, 29, plies TF-14 TA-10, plies 30, 31, 32, plies TF-15 TA-11, plies 33, 34, 35, plies TF-16, TA-12, and ply 36 per Table 9-1. Preply after each ply of Ti as a minimum.

19. Repeat Step 6.

20. Repeat Step 7.

21. Repeat Step 8.

22. Lay up 18 sheets of unidirectional GY-70/934 to prepare all gores needed for plies 36 to 54. Record batch and roll numbers of all prepreg used in layup.

23. Lay up plies 37, 38, plies TF-17, TA-13, plies 39, 40, 41, plies TF-18, TF-14, plies 42, 43, 44, plies TF-19, TA-15, and ply 45, per Table 9-1. Preply after each ply of Ti as a minimum.

24. Repeat Step 6.

25. Repeat Step 7.

26. Repeat Step 8.

27. Lay up plies 46, 47, plies TF-20, TA-16 plies 48, 49, ply TF-21, ply 50 ply TA-17, ply 51, ply TF-22, plies 52, 53, plies TF-23, TA-18, and ply 54 per Table 9-1. Preply after each ply of Ti as a minimum.

28. Repeat Step 6.

29. Repeat Step 7.

30. Repeat Step 8.

31. Lay up 18 sheets of unidirectional GY-70/934 to prepare all gores needed for plies 55-76. Record batch and roll numbers of all prepreg used in layup.

32. Lay up ply 55, ply TF-24, ply 56, ply TA-19, ply 57, ply TF-25, plies 58, 59, plies TF-26, TA-20, plies 60, 61, ply TF-27, ply 62,ply TA-21, and ply 63 per Table 9-1. Preply after each ply of Ti as a minimum.

33. Repeat Step 6.

34. Repeat Step 7.

35. Repeat Step 8.

36. Lay up ply TF-28, plies 64, 65, plies TF-29, TA-22, plies 66, 67, ply TF-30, ply 68, ply TA-23, ply TF-31, plies 70, 71, plies TF-32, TA-24, and ply 72 per Table 9-1. Preply after each ply of Ti as a minimum.

37. Repeat Step 6.

38. Repeat Step 7.

39. Repeat Step 8.

40. Lay up ply 73, plies TF-33, TA-25, and plies 74 to 76 per Table 9-1. Preply after each ply of Ti as a minimum.

41. Remove protractors.

42. Apply bleeder system consisting of one ply of porous, Teflon-coated glass separator, one ply of style 120 glass fabric, and six plies of style 7581 glass fabric. Apply a 1/8-inch thick rubber overpress followed by three plies of style 1534 glass fabric to serve as a vent. Place two thermocouples in the edge of the laminate and one on the tool. Bag for cure.

43. Cure as follows: Apply a minimum of 24 inches of mercury on the bag at RT, hold for a minimum of 30 minutes, heat the part in autoclave at a rate of 2 to 4F/minute to 250 ± 10F, hold at that temperature for 45 ± 5 minutes, apply 100 psig autoclave pressure in less than 5 minutes, hold an additional 45 + 5 minutes, heat the part at a rate of 2 to 4F/minute to 350 ± 10F, hold for 120 minutes, and cool the part at a rate not to exceed 5F/minute under vacuum and pressure.

44. Debag and remove part from tool.

45. Machine cone per drawing SK-ATI-009.

9.2 EQUIPMENT RING FABRICATION PROCEDURE

1. Obtain T300/934 for all gores needed for lay up of one equipment ring. Record batch and roll numbers of all prepreg used in the lay up.

2. Remove flange from bulk graphite tool. Apply FreKote 33 to tool and bake for one hour at 300F, repeat three times, reattach flange and attach propractor.

3. Lay up module 1 (0, 45, 90, 135, 135, 90, 45, 0). As a minimum preply after every other ply. Cut to gore size per Table 9-2.

4. Lay up module 2 (0, 45, 90, 135, 135, 90, 45, 0). As minimum preply after every other ply. Cut to gore size per Table 9-2.

5. Lay up module 3 (0, 45, 90, 135, 135, 90, 45, 0). As a minimum preply after every other ply. Cut to gore size per Table 9-2.

6. Apply one ply of porous Teflon-coated glass cloth over the lay up. Apply 12 plies of style 7581 glass fabric, followed by 1/8-inch rubber overpress, apply three plies of style 1534 glass fabric as vent, place two thermocouples in the edge of the laminate and one on the tool. Bag for precompaction.

7. Precompact as follows: Apply a minimum of 24 inches of mercury, heat in an autoclave at 2 to 5 F/Minute to 160 $\pm$ 5F, apply 50 psig autoclave pressure, hold 15 to 20 minutes, and cool under vacuum and pressure to below 100F at a rate not to exceed 5F/minute.

8. Remove bag, vent, overpress, bleeder fabric, and Teflon-coated glass cloth.

9. Lay up module 4 (0, 45,90, 135, 135, 90, 45, 0). As a minimum preply after every other ply. Cut to gore size per Table 9-2.

10. Lay up module 5 (0, 45, 90, 135, 135, 90, 45, 0). As a minimum preply after every other ply. Cut to gore size per Table 9-2.

11. Lay up module 6 (0, 45, 90, 135, 135, 90, 45, 0). As a minimum preply after every other ply. Cut to gore size per Table 9-2.

12. Repeat Step 6.

13. Repeat Step 7.

14. Repeat Step 8.

15. Lay up module 7 (0, 45, 90, 135, 135, 90, 45, 0). As a minimum preply after every other ply. Cut to gore size per Table 9-2.

16. Lay up module 8 (0, 45, 90, 135, 135, 90, 45, 0). As a minimum preply after every other ply. Cut to gore size per Table 9-2.

17. Lay up module 9 (0, 45, 90, 135, 135, 90, 45,0). As a minimum preply after every other ply. Cut to gore size per Table 9-2.

18. Repeat Step 6.

19. Repeat Step 7.

20. Repeat Step 8.

21. Lay up module 10 (0, 45,90, 135, 135, 90, 45,0). As a minimum preply after every other ply. Cut to gore size per Table 9-2.

22. Lay up module 11 (0, 45,90, 135, 135, 90, 45, 0). As a minimum preply after every other ply. Cut to gore size per Table 9-2.

23. Lay up module 12 (0, 45, 90, 135, 135, 90, 45,0). As a minimum preply after every other ply. Cut to gore size per Table 9-2.

24. Repeat Step 6.

25. Repeat Step 7.

26. Repeat Step 8.

27. Lay up module 13 (0, 45,90, 135, 135, 90, 45, 0). As a minimum preply after every other ply. Cut to gore size per Table 9-2.

28. Lay up module 14 (0, 45, 90, 135, 135, 90, 45, 0). As a minimum preply after every other ply. Cut to gore size per Table 9-2.

29. Lay up module 15 (0, 45, 90, 135, 135, 90, 45, 0). As a minimum preply after every other ply. Cut to gore size per Table 9-2.

30. Repeat Step 6.

31. Repeat Step 7.

32. Repeat Step 8.

33. Lay up module 16 (0, 45, 90, 135, 135, 90, 45, 0). As a minimum preply after every other ply. Cut to gore size per Table 9-2.

34. Lay up module 17 (0, 45, 90, 135, 135, 90, 45, 0). As a minimum preply after every other ply. Cut to gore size per Table 9-2.

35. Lay up module 18 (0, 45, 90, 135, 135, 90, 45, 0). As a minimum preply after every other ply. Cut to gore size per Table 9-2.

36. Lay up module 19 (0, 45, 90, -45). As a minimum preply after every other ply. Cut to gore size per Table 9-2.

37. Lay up module 20 (-45, 90). As a minimum preply after every other ply. Cut to gore size per Table 9-2.

38. Lay up module 21 (45, 0). As minimum preply after every other ply gore size per Table 9-2.

39. Apply bleeder system consisting of one ply of porous, Teflon-coated glass separator, one ply of style 120 glass fabric, and three plies of style 7581 glass fabric. Apply a 1/8-inch thick rubber overpress followed by three plies of style 1534 glass fabric to serve as a vent. Place two thermocouples in the edge of the laminate and one on the tool. Bag for cure.

40. Cure as follows: Apply a minimum of 24 inches of mercury on the bag at RT, hold for a minimum of 30 minutes, heat the part in autoclave at a rate of 2 to 4F/minute to 250 $\pm$ 10F, hold at that temperature for 45 $\pm$ 5 minutes, apply 100 psig autoclave pressure in less than 5 minutes, hold an additional 45 $\pm$ 5 minutes, heat the part at a rate of 2 to 4F/minute to 350 $\pm$ 10F, hold for 120 minutes, and cool the part at a rate not to exceed 5F/minute under vacuum and pressure.

41. Debag and remove part from tool.

42. Machine and install inserts per drawing SK ATI-004.

9.3 ASSEMBLY PROCEDURE

1. Obtain equipment ring and frustum from machine shop.

2. Verify dimensions.

3. Obtain locating fixture, prefit equipment ring into frustum.

4. Verify location and determine required bond line thickness.

5. Mark location of equipment ring on inside of frustum.

6. Remove equipment.

7. Abraid surfaces to be bonded with Scotchbrite. Abraid 0.25 inch past equipment ring EOP (end of part) on frustum.

8. Apply EA934 to mating surfaces.

9. Locate equipment ring in frustum using locating fixture. Prefit predetermined thicknesses of wire (operation 4) on frustum surface.

10. Clean excess EA934 off of equipment ring, frustum and locating fixture.

11. Cure undisturbed for a minimum of 48 hours.

12. Remove locating fixture.

13. Verify dimensions.

14. Submit to test.

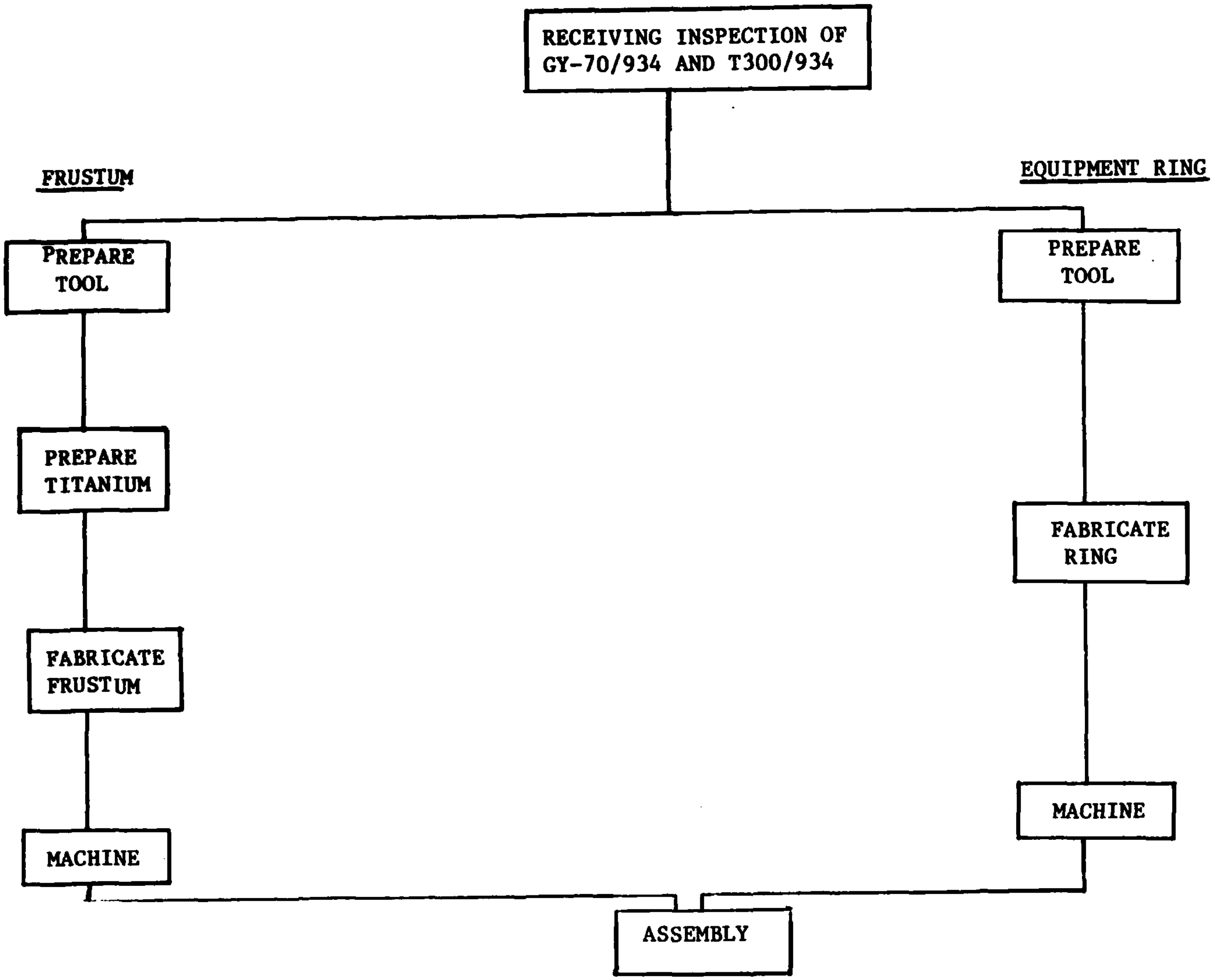


Figure 9-1. Fabrication Sequence for Frustum Assembly

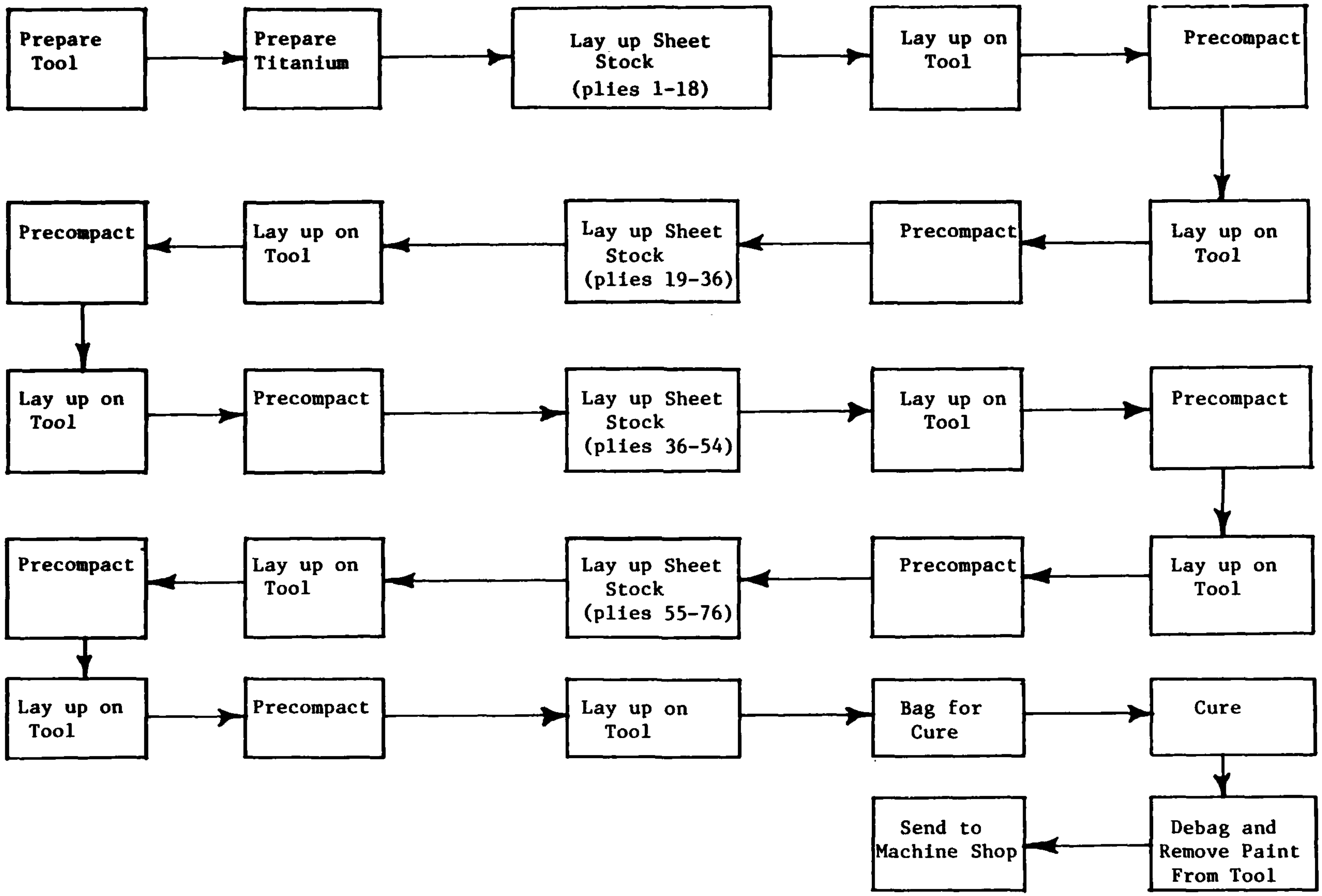


Figure 9-2. Detail Fabrication Breakdown for Full Size Frustum

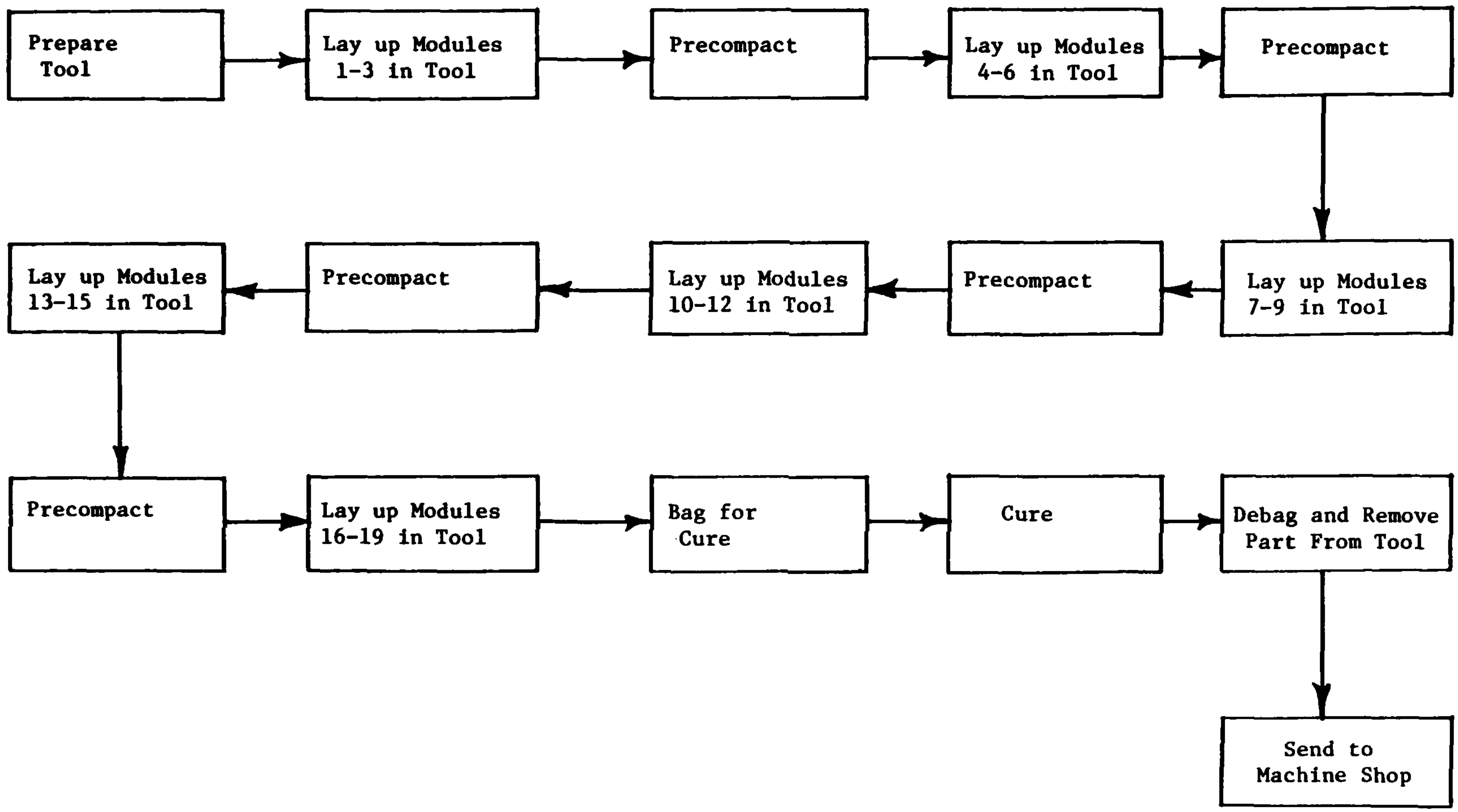


Figure 9-3. Detail Fabrication Breakdown for Equipment Ring

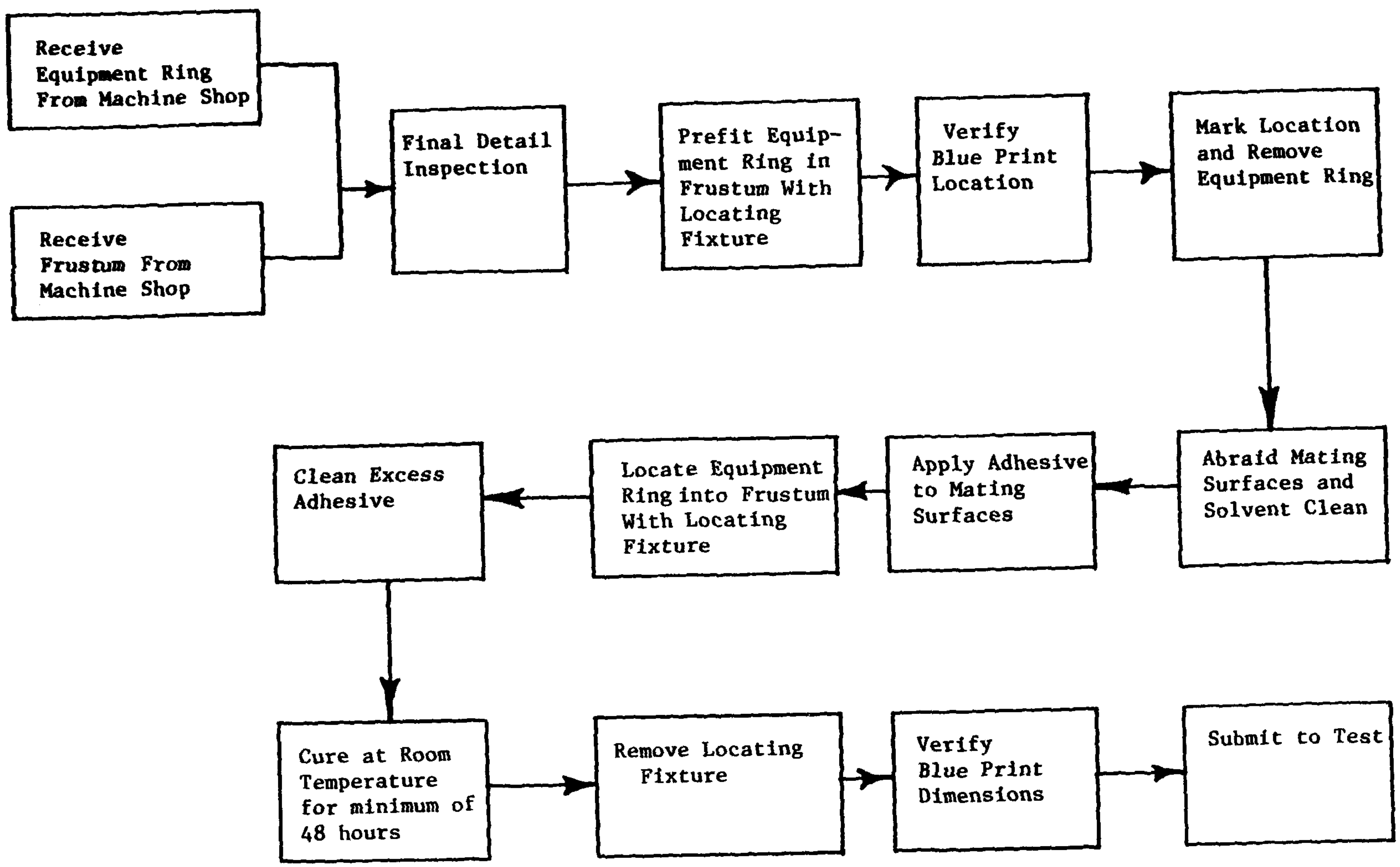


Figure 9-4. Assembly of Equipment Ring and Frustum

Table 9-1. Orientation and Size of Gore Section for a Full-Scale ATI Frustum

Ply No.	Orientation of Ply	α	Wrap Angle	Gore Size (see sketch)			
				A	B	C	L
Outside							
1	0	0°	30	2.053	4.077	-	35.41
2	0	15°	30	2.051	4.073	-	
3	45	7°30'	90	6.145	12.213		
TF-1	-	22°30'	30	2.045	-	2.483	7.6
TA-1	-	22°30'	30	-	4.068	3.72	6.05
4	90	5°	90	6.130	12.197	-	
5	135	20°	90	6.122	12.189		
TF-2	-	12°30'	30	2.038	-	2.475	7.6
TA-2	-	12°30'	30	-	4.060	3.713	6.05
6	90	27°30'	90	6.106	12.174	-	
7	45	17°30'	90	6.098	12.166		
TF-3	-	2°5'	30	2.030	-	2.467	7.6
8	0	25°	30	2.027	4.052		
TA-3	-	2°5'	30		4.050	3.703	6.05
9	0	10°	30	2.025	4.047		
TF-4	-	0°	30	2.022	-	2.438	7.24
10	0	15°	30	2.019	4.045		
11	135	7°30'	90	6.051	12.126		
TF-5	-	22°30'	30	2.014	-	2.431	7.24
TA-4	-	22°30'	30	-	4.039	3.713	5.69
12	0	5°	30	2.012	4.037		
13	0	20°	30	2.007	4.034		
TF-6	-	12°30'	30	2.006	-	2.423	7.24
14	0	27°30'	30	2.004	4.031		
TA-5	-	12°30'	30	-	4.029	3.703	5.69
15	45	17°30'	90	6.004	12.079		
TF-7		2°30'	30	1.999	-	2.396	6.91
16	0	25°	30	1.996	4.024		
17	0	10°	30	1.992	4.021		
TF-8	-	0°	30	1.991	-	2.388	6.91
TA-6	-	0°	30	-	4.019	3.690	5.69
18	135	15°	90	5.965	12.048		
19	0	7°30'	30	1.985	4.013		
TF-9	-	22°30'	30	1.983	-	2.387	6.91
20	0	5°	30	1.980	4.010		
TA-7	-	12°30'	30	-	4.008	3.700	5.33
21	135	20°	90	5.933	12.016		
TF-10	-	12°30'	30	1.975	-	2.354	6.58
22	0	27°30'	30	1.972	4.003		
23	0	17°30'	30	1.970	4.000		
TF-11	-	2°30'	30	1.967	-	2.345	6.58
TA-8	-	2°30'	30	-	3.997	3.689	5.33
24	45	25°	90	5.894	11.985		
25	0	10°	30	1.962	3.992		
TF-12	-	0°	30	1.959	-	2.338	6.58
26	0	15°	30	1.957	3.989		

Table 9-1. Orientation and Size of Gore Section for a Full-Scale ATI Frustum

Ply No.	Orientation of Ply	α	Wrap Angle	A	B	C	L
TA-9	-	22°30'	30	-	3.987	3.679	5.33
27	0	7°30'	30	1.954	3.984		
TF-13	-	22°30'	30	1.952	-	2.330	6.58
28	135	5°	90	5.847	11.945		
29	0	20°	30	1.945	3.979		
TF-14	-	12°30'	30	1.943	-	2.303	6.25
TA-10	-	12°30'	30	-	3.976	3.691	4.98
30	0	7°30'	30	1.940	3.974		
31	0	17°30	30	1.938	3.971		
32	45	2°30'	90	5.808	11.906		
TF-15	-	25°	30	1.933	-	2.293	6.25
TA-11	-	25°	30	-	3.966	3.681	4.98
33	90	10°	90	5.792	11.890		
34	135	0°	90	5.784	11.883		
35	90	15°	90	5.776	11.875		
TF-16	-	7°30'	30	1.923	-	2.282	6.25
TA-12	-	7°30'	30	-	3.955	3.670	4.98
36	45	22°30'	90	5.761	11.859		
37	0	5°	30	1.917	3.950		
38	0	20°	30	1.915	3.947		
TF-17	-	12°30'	30	1.912	-	2.272	6.25
TA-13	-	12°30'	30	-	3.945	3.660	4.98
39	0	27°30'	30	1.909	3.942		
40	0	17°30'	30	1.907	3.940		
41	45	2°30'	90	5.713	11.812		
TF-18	-	25°	30	1.902	-	2.242	5.92
TA-14	-	25°	30	-	3.935	3.670	4.62
42	90	10°	90	5.698	11.796		
43	135	0°	90	5.690	11.788		
44	90	15°	90	5.682	11.781		
TF-19	-	7°30'	30	1.891	-	2.232	5.92
TA-15	-	7°30'	30	-	3.924	3.659	4.62
45	45	22°30'	90	5.662	11.765		
46	0	5°	30	1.885	3.919		
47	0	20°	30	1.884	3.916		
TF-20	-	12°30'	30	1.881		2.222	5.92
TA-16	-	12°30'	30	-	3.913	3.649	4.62
48	0	27°30'	30	1.878	3.911		
49	135	17°30'	90	5.627	11.726		
TF-21	-	2°30'	30	1.873	-	2.214	5.92
50	0	25°	30	1.870	3.906		
TA-17	-	2°30'	30	-	3.903	3.686	4.26
51	0	10°	30	1.868	3.900		
TF-22	-	0°	30	1.865	-	2.187	5.59
52	0	15°	30	1.862	3.898		
53	45	7°30'	90	5.580	11.686		
TF-23	-	22°30'	30	1.857	-	2.179	5.59
TA-18	-	22°30'	30	-	3.892	3.675	4.26
54	0	5°	30	1.855	3.890		
55	0	20°	30	1.852	3.887		
TF-24	-	12°30'	30	1.849	-	2.171	5.59
56	135	27°30'	90	5.541	11.655		

Table 9-1. Orientation and Size of Gore Section for a Full-Scale ATI Frustum

Ply No.	Orientation of Ply	α	Wrap Angle	A	B	C	L
TA-19	-	12°30'	30	-	3.882	3.665	4.26
57	0	17°30'	30	1.844	3.879		
TF-25	-	2°30'	30	1.842	-	2.145	5.26
58	0	25°	30	1.839	3.877		
59	135	10°	90	5.509	11.623		
TF-26	-	0°	30	1.834	-	2.137	5.26
TA-20	-	0°	30	-	3.872	3.646	3.91
60	0	15°	30	1.831	3.869		
61	0	7°30'	30	1.828	3.866		
TF-27	-	22°30'	30	1.826	-	2.129	5.26
62	45	5°	90	5.470	11.592		
TA-21	-	15°	30	-	3.861	3.636	3.91
63	0	20°	30	1.821	3.858		
TF-28	-	12°30'	30	1.818	-	2.102	4.93
64	0	27°30'	30	1.816	3.856		
65	0	17°30'	30	1.813	3.854		
TF-29	-	2°30'	30	1.810	-	2.094	4.93
TA-22	-	2°30'	30	-	3.851	3.626	3.91
66	135	25°	90	5.423	11.545		
67	0	10°	30	1.805	3.845		
TF-30	-	0°	30	1.802	-	2.086	4.93
68	0	15°	30	1.799	3.843		
TA-23	-	0°	30	-	3.840	3.637	3.55
69	0	7°30'	30	1.797	3.838		
TF-31	-	22°30'	30	1.795	-	2.059	4.60
70	45	5°	90	5.376	11.506		
71	90	20°	90	5.368	11.498		
TF-32	-	12°30'	30	1.787	-	2.051	4.60
TA-24	-	12°30'	30	-	3.830	3.627	3.55
72	135	27°30'	90	5.352	11.482		
73	90	17°30'	90	5.345	11.474		
TF-33	-	2°30'	30	1.779	-	2.044	4.60
TA-25	-	2°30'	30	-	3.822	3.619	3.55
74	45	25°	90	5.329	11.459		
75	0	10°	30	1.773	3.817		
76	0	0°	30	1.747	3.814		
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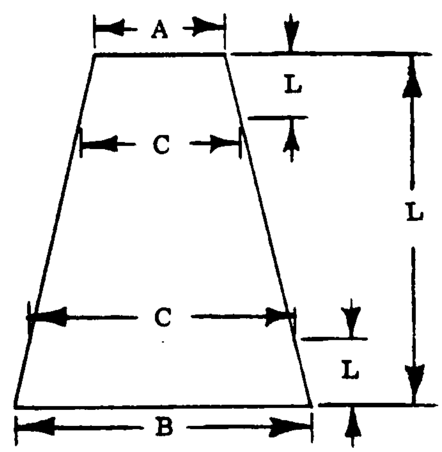
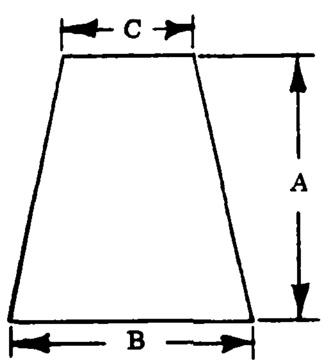


Table 9-2. Gore Sizes for Equipment Ring

Module*	A	B	C
1	4.17	6.18	5.71
2	3.98	6.14	5.68
3	3.79	6.10	5.66
4	3.60	6.06	5.64
5	3.41	6.02	5.62
6	3.22	5.97	5.61
7	3.03	5.93	5.59
8	2.84	5.89	5.57
9	2.65	5.85	5.54
10	2.46	5.81	5.52
11	2.27	5.76	5.50
12	2.08	5.72	5.48
13	1.89	5.68	5.46
14	1.70	5.64	5.45
15	1.50	5.59	5.42
16	1.31	5.56	5.40
17	1.12	5.51	5.38
18	0.93	5.47	5.36
19	4.19	5.45	5.68
20	4.19	5.44	5.67
21	4.19	5.43	5.66

*See SK-ATI-004 Full-Size Ring



SECTION 10

CONCLUSIONS

All critical areas of the ATI guidance and control section have been demonstrated by testing to meet design load conditions. The margins of safety are small, typical of a minimum weight design. The following conclusions are drawn as a result of this program:

1. Testing of spliced specimens has shown that use of prepreg gore sections in fabricating frusta has negligible effect on modulus and strength.
2. The wedge shaped graphite/epoxy equipment ring concept has been demonstrated experimentally and analytically.
3. The forward joint concept incorporating antenna cutouts was demonstrated experimentally to exceed design load requirements.
4. The full-scale aft joint was shown experimentally to exceed design requirements.

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SECTION 11

RECOMMENDATIONS

The advanced terminal interceptor substructural material program is ready to proceed to the manufacture and testing of full-scale guidance and control sections. The following recommendations are proposed for a logical follow-on program.

1. Fabricate forebody sections utilizing tooling procured and the design finalized under this contract (DAAG46-79-C-0081).

2. Inspect the frusta ultrasonically and test the assembled sections in accordance with the test plan developed under contract DAAG46-78-C-0056 and given in Report AMMRC TR80-44.

3. Design and assemble test fixtures to conduct full-scale forebody testing.

4. Analyze test data and compare performance to predictions.

5. Design flightweight test structure.

6. Modify manufacturing process plan to make it pertinent for flightweight test structure.

7. Fabricate one flightweight forebody.

8. Develop an alternate ultra-high-modulus prepreg source for use in ATI forebodies based on pitch P-75S fiber.

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SECTION 12

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Army Materials and Mechanics Research Center
Watertown, Massachusetts 02172
DEVELOPMENT OF ADVANCED INTERCEPTOR
SUBSTRUCTURAL MATERIAL
N.R. Adsit, and J. Hertz
General Dynamics Convair Division

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